DOT/FAA/AR-02/98

Office of Aviation Research
Washington, D.C. 20591

Design and Fabrication of a Head Injury Criteria-Compliant Bulkhead

December 2002

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-02/98		

4. Title and Subtitle	5. Report Date
DESIGN AND FABRICATION OF A HEAD INJURY CRITERIA-COMPLIANT BULKHEAD	December 2002
	6. Performing Organization Code
7. Author(s) Hamid Lankarani	8. Performing Organization Report No.
9. Performing Organization Name and Address National Institute for Aviation Research Wichita State University 1845 N. Fairmount Wichita, KS 67260-0093	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 00-C-WSU - 00 Amendment Number 3 & 29
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591	13. Type of Report and Period Covered Final Report From 07/00 to 12/01 14. Sponsoring Agency Code ANM-106

15. Supplementary Notes

Program Manager: Gary Frings, Federal Aviation Administration, William J. Hughes Technical Center
Technical Monitor: Dr. Tong Vu, Federal Aviation Administration, William J. Hughes Technical Center.

16. Abstract

The certification of aircraft requires engineers to demonstrate that a head strike into any one of several cabin furnishings complies with the head injury criteria (HIC) requirements specified in 14 CFR 23.562 and 14 CFR 25.562. The problem encountered in the certification of 16-g airline seats, referred to as the front-row HIC problem, occurs for seats located directly behind bulkheads or cabin class dividers. This research addresses the design and fabrication of HIC-compliant bulkheads. The compliance with HIC has posed a significant problem for the airlines and the manufacturers of jet transports due to high costs and schedule overruns during the development and certification of aircraft seats. The goal of this study is to demonstrate that there is a potential solution for the bulkhead HIC problem. The research is also aimed at generating a detailed methodology for the design and development of HIC-compliant bulkheads.

17. Key Words	18. Distribution Statement
Aircraft crashworthiness, Aircraft seat certification, HIC-compliant bulkhead, Biodynamic simulation, Head injury criteria, Bulkhead design methodology	This document is available to the public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		vii
1.	INTRODUCTION	1
2.	BASELINE STUDY AND HIC TESTS	1
3.	DESIGN CURVES FOR HIC ATTENUATION	4
4.	CANDIDATE HIC-COMPLIANT BULKHEADS	7
5.	DYNAMIC TESTS OF THE DESIGNED BULKHEADS	11
	5.1 Dynamic Test on a Series I Bulkhead	11
	5.2 Dynamic Tests on Series II Bulkheads	13
	5.3 Dynamic Tests on Series III Bulkheads	15
6.	DESIGN METHODOLOGY FOR THE DEVELOPMENT OF HIC-COMPLIANT BULKHEADS	18
7.	SUMMARY	20
8.	REFERENCES	20

APPENDICES

A—Data Analysis Procedure
B—Data Sheets for Sled Tests 97191-001 and 97191-002
C—Data Sheets for Sled Test Series 01008
D—Design Methodology Applied to Thin Aluminum Panels
E—Data Sheet for Sled Test 96288-004

LIST OF FIGURES

Figure		Page
1	Idealized Triangular Pulse and Actual Deceleration Pulse	2
2	Seat Setback Measurement Convention for Sled Tests	2
3	Full-Scale Sled Test Setup With Cabin Class Divider Panel	3
4	Kinematics of Baseline Full-Scale Sled Test 97191-002	3
5	Resultant Head c.g. Acceleration Profile for Full-Scale Sled Tests 97191-001 and -002	4
6	Sign Convention for Head Impact Angle Measurement	4
7	MADYMO Biodynamic Model	5
8	Methodology Used for Validation	5
9	Resultant Head c.g. Acceleration Comparison of Full-Scale Sled Test With Analytical Model	6
10	Derived Stiffness Curves From Parametric Studies for 33- and 35-in. Seat Setback Distances	7
11	Bulkhead Honeycomb Cores and Face Sheet	7
12	Honeycomb Bulkhead Panels	8
13	Bulkhead Panel Layup	9
14	Static Testing of Honeycomb Bulkhead	9
15	Load Deflection Characteristics and Stiffness Values of Series I and II Bulkheads	10
16	Load Deflection Characteristics and Stiffness Value of Series III Bulkhead	10
17	Setup for Full-Scale Sled Test 01008-3 on a Series I Bulkhead	11
18	ATD Kinematics for Sled Test 01008-3	12
19	Resultant Head c.g. Acceleration and HIC Value for a Series I Bulkhead at 35-in. Seat Setback Distance (Test 01008-3)	12
20	Setup for Full-Scale Sled Test 01008-8 on a Series II Bulkhead	13
21	ATD Kinematics for Sled Test 01008-8	14

22	Resultant Head c.g. Acceleration and HIC Value for a Series II Bulkhead at 35-in. Seat Setback Distance (Test 01008-8)	14
23	Resultant Head c.g. Acceleration and HIC Value for a Series II Bulkhead at 33-in. Seat Setback Distance (Test 01008-9)	15
24	Setup for Full-Scale Sled Test 01008-13 on a Series III Bulkhead at 33-in. Seat Setback Distance	16
25	ATD Kinematics for Sled Test 01008-13	16
26	Resultant Head c.g. Acceleration and HIC Value for a Series III Bulkhead at 33-in. Seat Setback Distance (Test 01008-13)	17
27	Resultant Head c.g. Acceleration and HIC Value for a Series III Bulkhead at 35-in. Seat Setback Distance (Test 01008-14)	17
28	Design Methodology for HIC-Compliant Bulkhead	19
29	Stiffness of the Aluminum Panel and Bulkheads on the Design Curves	19

LIST OF TABLES

Table		Page
1	Baseline Full-Scale Sled Test Results	3
2	Sample Validation Results	6
3	Properties of the Different Bulkhead Series	8
4	Static Test Results for the Bulkhead Series	10
5	Summary of the Test Result for a Series I Bulkhead	13
6	Summary of the Test Results for Series II Bulkheads	15
7	Summary of the Test Results for Series III Bulkheads	18
8	Summary of Results for Test Series 01008	18

EXECUTIVE SUMMARY

The need for head injury protection has been addressed with the inclusion of the head injury criteria (HIC) in the dynamic seat certification requirements specified in paragraph 562 of Title 14 Code of Federal Regulations (CFR) Parts 23, 25, 27, and 29. Compliance with the HIC poses a significant problem for many segments of the aircraft industry. The certification requires engineers to demonstrate that a head strike into any one of several cabin furnishings complies with an HIC threshold of 1000. The problem encountered in the certification of 16-g seats, referred to as the front row HIC problem, occurs for seats located behind bulkheads and cabin class dividers. These structures are typically stiff and, hence, produce unacceptably large HIC values. This research is directed towards the design and fabrication of a bulkhead for HIC attenuation that will meet the industry's appearance and aesthetic requirements as well.

The report addresses the study conducted on various honeycomb materials for HIC attenuation. MADYMO biodynamic simulations, supported by simple quasi-static tests, were developed for the design of HIC-compliant bulkheads which effectively attenuated HIC below the injury levels. The MADYMO models were used for a parametric study of the effects of stiffness and strength of the bulkhead on HIC levels and to develop design heuristics for the fabrication of HIC-compliant bulkheads. New bulkhead designs and materials were derived, statically tested for the load deflection properties, and the results were compared with design curves. The compliance of the new bulkheads for HIC was then assessed by conducting full-scale dynamic sled tests on these structures at 33-inch and 35-inch seat setback distances. This study also produced a detailed methodology for the design and development of HIC-compliant bulkheads.

1. INTRODUCTION.

The compliance with the head injury criteria (HIC) specified in Title 14 Code of Federal Regulations (CFR) Part 23.562 [1] and Part 25.562 [2] poses a significant problem for many segments of the aerospace industry. Airlines and manufacturers of jet transports have experienced high costs and significant schedule overruns during the development and certification of 16-g seats because of the difficulties encountered in meeting this requirement.

Problems in the certification of 16-g airline seats (referred to as the front-row HIC problem) occur for seats located directly behind bulkheads or cabin class dividers. These structures are typically both stiff and strong and therefore produce very high HIC values as a result of head impacts. The industry has addressed this problem using a number of approaches with mixed results. Technology-based solutions include the dynamic seat testing development of articulated seats and y-belt restraint systems. These approaches range from requesting an exemption to the rule to removing one row of seats from the aircraft. None of these solutions has been judged to be entirely satisfactory by the airlines, airframe manufacturers, or the Federal Aviation Administration (FAA). Articulated seats are expensive and heavy and are also objectionable to the airlines because of the maintenance problems posed in supporting a nonstandard piece of equipment. The use of y-belts also creates a similar maintenance problem as well as generating concern about the safety of applying large restraint system forces to soft abdominal tissues. Finally, removing a row of seats from a transport aircraft creates a significant economic burden to airlines.

The goal of this research is to demonstrate that there are potential solutions for the bulkhead HIC problem. The project is also aimed at generating a design methodology for the development of bulkheads for HIC attenuation.

2. BASELINE STUDY AND HIC TESTS.

Dynamic full-scale sled tests 97191-001 and 97191-002 were conducted at the Impact Dynamics Laboratory of the National Institute for Aviation Research (NIAR) to measure the head accelerations of a Hybrid-II Anthropomorphic Test Dummy (ATD) as specified in 14 CFR 25.562. The tests were conducted at different seat setback distances using some typical production cabin class dividers, which had Nomex honeycomb core with fiberglass facings and were covered with carpet typically used in aircraft applications. The purpose of these tests was to quantify the kinematics of the ATD such as head impact angle and velocity as well as the resulting HIC for typical cabin class divider panels at different distances from the seat. The NIAR sled is a pneumatically propelled, deceleration-type sled. As per the CFR, a triangular deceleration pulse with a peak of 16 g's and a rise time of 90 ms was targeted for all the tests. The ideal pulse shape and the actual sled test deceleration pulse for the two baseline tests are shown in figure 1.

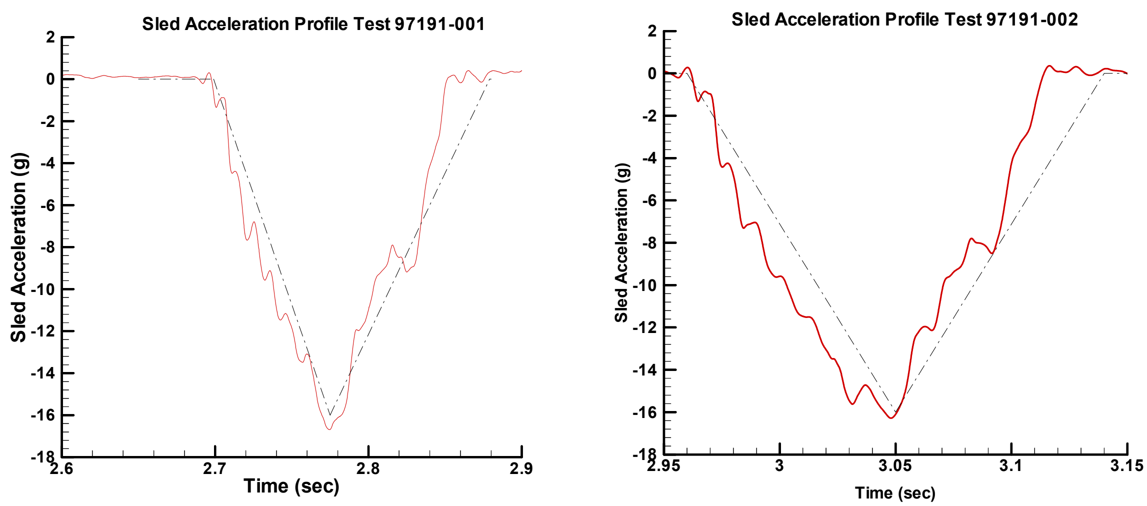


FIGURE 1. IDEALIZED TRIANGULAR PULSE AND ACTUAL DECELERATION PULSE

Seat setback distance is defined as the horizontal distance between the seat reference point, i.e., the intersection point between the seat back and the seat pan, and the outer surface of the bulkhead. An iron seat fabricated from 2-in.-square steel tubing was used in the dynamic sled test. To maximize the energy transferred to the head, no yaw was given to the seat in these tests. The seat back and seat pan were constructed from 1/8-in. aluminum plate. The geometry of the seat, shown in figure 2, is representative of a typical airline economy class seat with the seat back fixed in the upright position. Seat cushions were not used during the test. A typical polyester seat belt was used during this program. Figure 3 shows the sample full-scale sled test setup with cabin class divider panel.

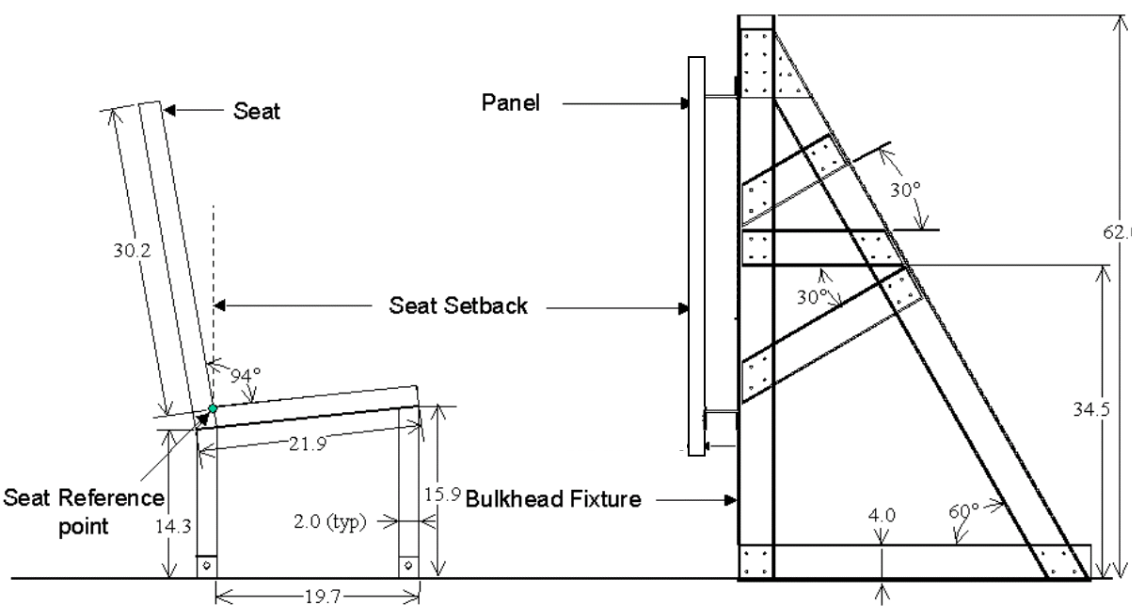


FIGURE 2. SEAT SETBACK MEASUREMENT CONVENTION FOR SLED TESTS

FIGURE 3. FULL-SCALE SLED TEST SETUP WITH CABIN CLASS DIVIDER PANEL

A triaxial accelerometer was mounted at the center of gravity (c.g.) of the ATD head to determine the resultant head acceleration. Figure 4 shows the kinematics of the baseline full-scale sled test 97191-002. Test results are summarized in table 1. Figure 5 shows the resultant head c.g. acceleration profile for the test series.

FIGURE 4. KINEMATICS OF BASELINE FULL-SCALE SLED TEST 97191-002

TABLE 1. BASELINE FULL-SCALE SLED TEST RESULTS

Test	Test Pulse (g)	Seat Setback Distance (in.)	Head Impact Angle (degrees)	Head Impact Velocity (ft/sec)	HIC	HIC Window $\Delta t = t_2 - t_1$ (ms)
97191-001	16.7	35	53	44.9	823	19.0
97191-002	16.3	34	42	45.3	1394	12.5

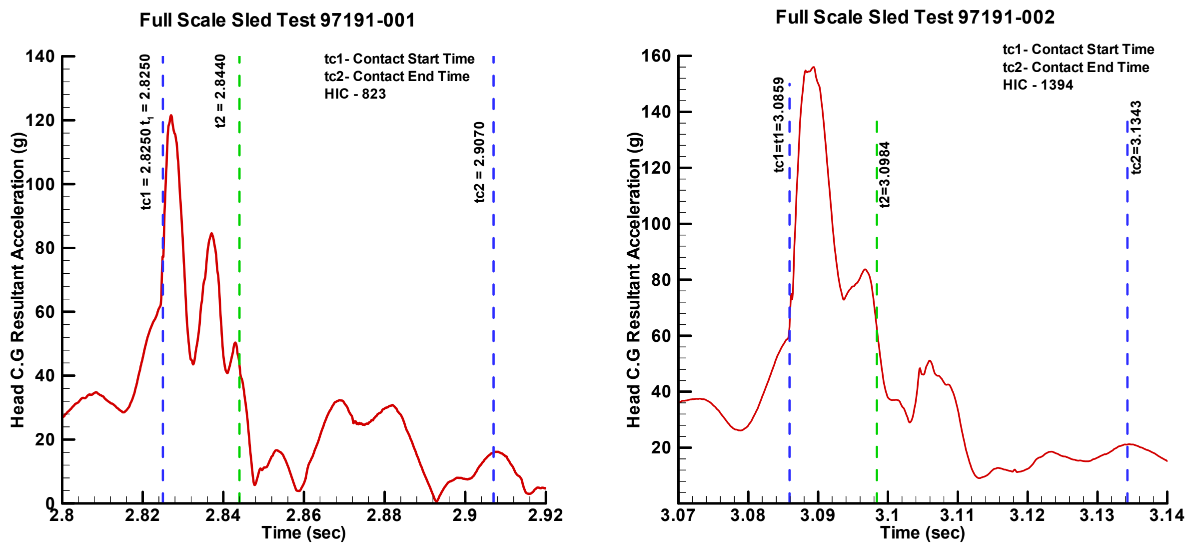


FIGURE 5. RESULTANT HEAD C.G. ACCELERATION PROFILE FOR FULL-SCALE SLED TESTS 97191-001 AND -002

The procedure used in calculating the various parameters is given in appendix A. The data for the tests are shown in appendix B. As observed, at 34-inch seat setback distance, the head impact angle is small and most of the energy of the head is transferred in the normal direction to the frontal structure, resulting in a high HIC (above the threshold). At 35-inch seat setback distance, the head impact angle is larger as the head moves both in the normal and tangential direction to the frontal structure. The sign convention for the head impact angle measurement is shown in figure 6.

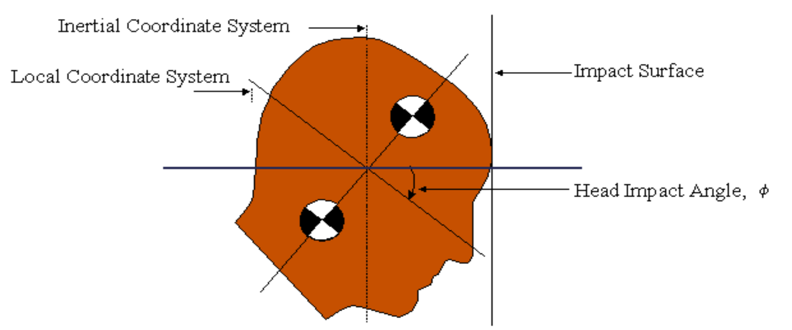


FIGURE 6. SIGN CONVENTION FOR HEAD IMPACT ANGLE MEASUREMENT

3. DESIGN CURVES FOR HIC ATTENUATION.

A MADYMO biodynamic model was used to establish design guidelines for developing energy absorbing HIC-compliant bulkheads. MADYMO possesses multibody dynamic and nonlinear finite element analysis capabilities as well as to robust tools for modeling restraint systems and contact surfaces representing arbitrary force-deflection characteristics of lap belts and shoulder harnesses. The contact algorithm allows the belts to slide over the occupant body. It also generates friction forces and normal forces in addition to the kinematics constraints. The

MADYMO biodynamic model is shown in figure 7 and has been validated during dynamic sled tests at 34-inch seat setback distance [3]. Figure 8 shows the methodology for the validation of the analytical model at 34-inch seat setback distance. Figure 9 and table 2 show a sample of the head acceleration comparison of the full-scale sled test and the analytical model results.

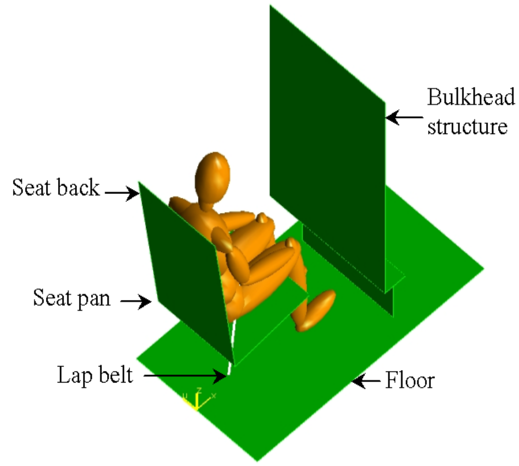


FIGURE 7. MADYMO BIODYNAMIC MODEL

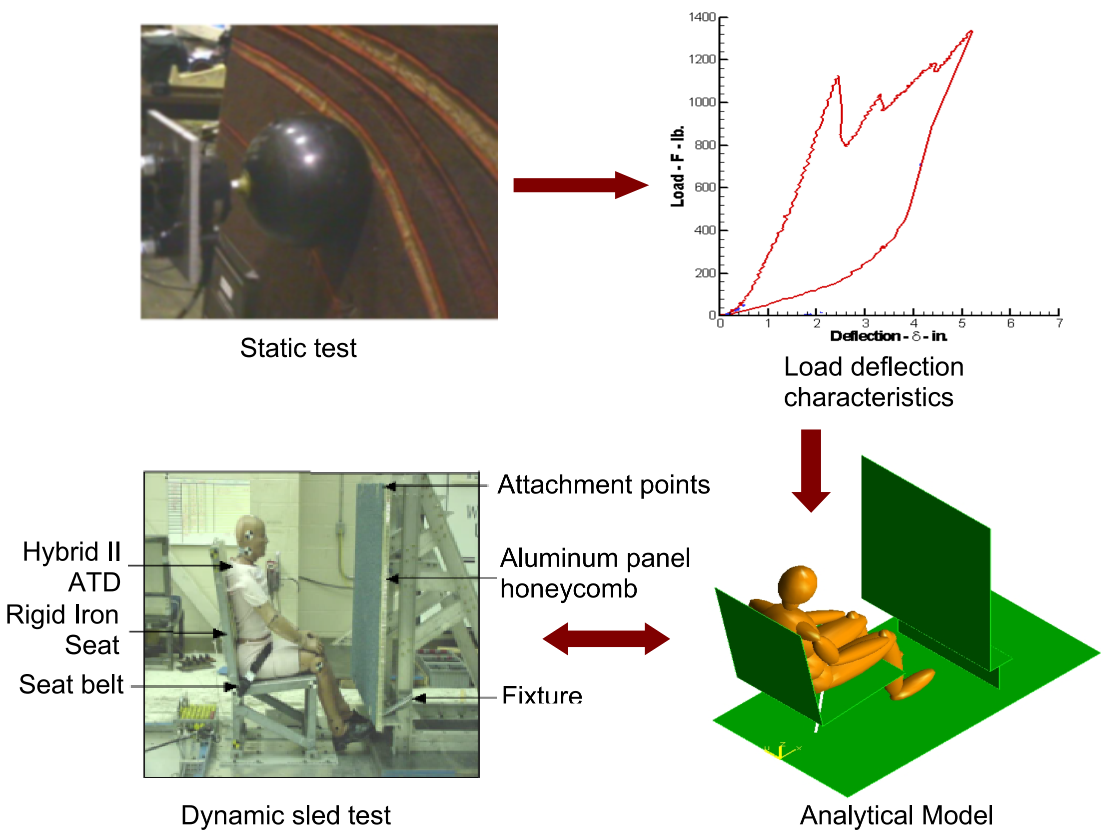


FIGURE 8. METHODOLOGY USED FOR VALIDATION

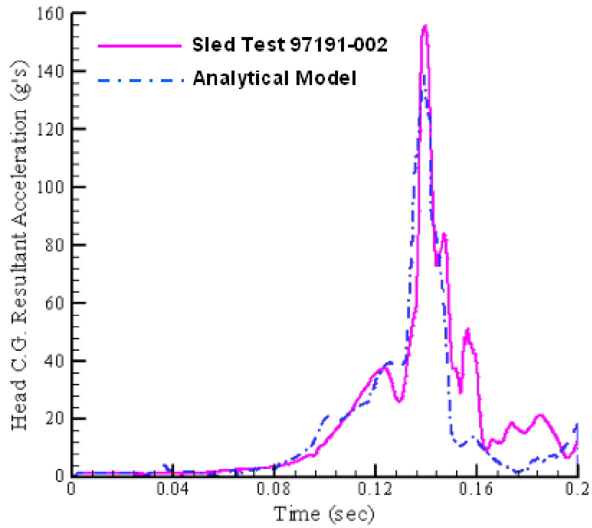


FIGURE 9. RESULTANT HEAD C.G. ACCELERATION COMPARISON OF FULL-SCALE SLED TEST WITH ANALYTICAL MODEL

TABLE 2. SAMPLE VALIDATION RESULTS

Test	Head Peak Acceleration (g)	Average Acceleration (g)	HIC	Δt (ms)
97191-02	156	106	1394	12.5
Analysis	144	101	1376	13.7

The analytical model represents the standard 50th percentile male Hybrid-II ATD and bulkhead geometry evaluated during the baseline dynamic tests. The bulkhead was modeled as a rigid plane with an assigned load deflection response, which was determined by the static tests. The contact force was defined as force acting on the head of the ATD in a direction normal to the bulkhead. The pelvic restraint was represented by a simple one-dimensional spring element. An additional plane was defined to represent the fixture beam positioned directly in front of the ATD's feet providing the boundary condition for the ATD's lower extremities. The contact forces between these planes and the appropriate ATD body segments were defined in terms of loading and unloading curves. The contact characteristics of the bulkhead plane were varied to simulate different material properties. The performance was characterized in terms of the expected HIC values.

The MADYMO model was then used to conduct a parametric study on the variation of HIC versus stiffness of the bulkhead material at the point of head impact. Figure 10 shows the derived stiffness curves (design curves) from the parametric studies for seat setback distances of 33 and 35 in. The derived stiffness curves indicate that the allowable threshold for the bulkhead stiffness at the point of head impact is 480 lb/in at 33-in. seat setback distance and 709 lb/in at 35-in. seat setback distances for the HIC below 1000.

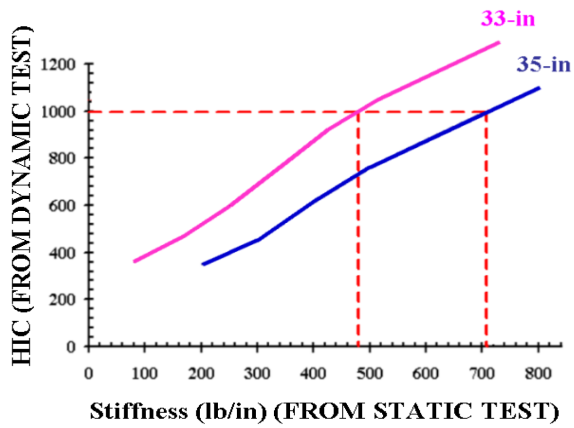
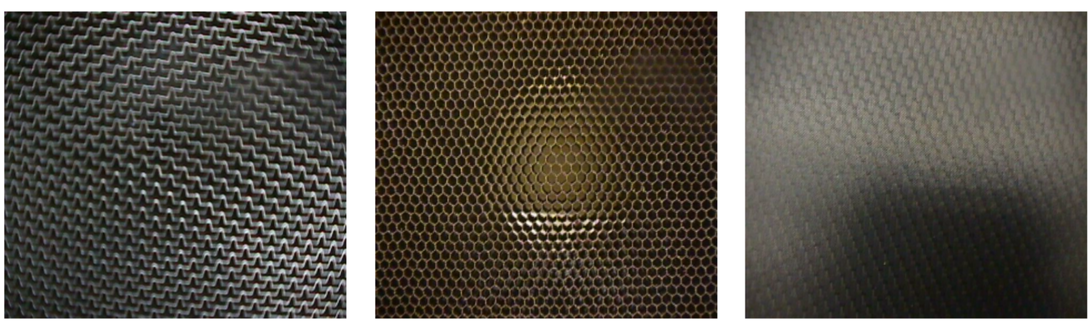


FIGURE 10. DERIVED STIFFNESS CURVES FROM PARAMETRIC STUDIES FOR 33- AND 35-in. SEAT SETBACK DISTANCES

4. CANDIDATE HIC-COMPLIANT BULKHEADS.

Candidate bulkheads were selected based on earlier experience in NIAR and FAA Civil Aero Medical Institute (CAMI) tests. The following parameters were considered for the selection of bulkhead material: (a) loading condition, (b) panel type, (c) physical/space constraints, (d) panel deflection, (e) crush strength, and (f) stiffness [4]. A sandwich structure of honeycomb core glued between two fiberglass face sheets was selected for the bulkheads. The honeycomb core was either metallic or nonmetallic and characterized by its stiffness that has to be below the threshold value specified in the design curves. Figure 11 shows a sample of the metallic and nonmetallic honeycomb cores and fiberglass face sheets for the bulkhead panels selected.



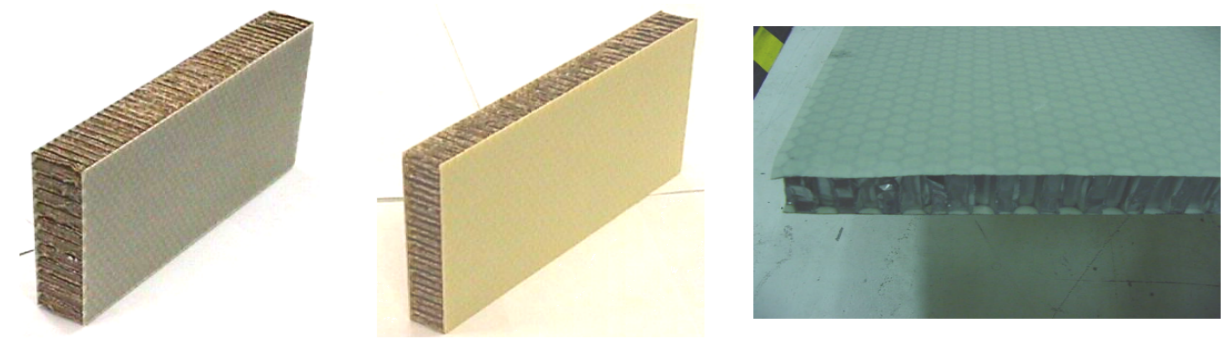
Aluminum Honeycomb Core Nomex Honeycomb Core Fiberglass Face Sheet

FIGURE 11. BULKHEAD HONEYCOMB CORES AND FACE SHEET

Based on bulkhead seat dynamic test data from CAMI and NIAR, the bulkhead panels selected for HIC compliance are listed below.

- Series I TEKLAM (N510) Phenolic/Nomex honeycomb panel
- Series II TEKLAM (N510 (E)) Epoxy/Nomex honeycomb panel
- Series III TEKLAM (Custom made) Aluminum honeycomb

The panels were selected based on manufacturer's information from the stiffest (series I) to the softest (series III). The panels are machined into 48- x 48-inch bulkheads to be mounted on the fixture. Figure 12 shows the honeycomb bulkhead panels. Table 3 summarizes properties of the different bulkhead series.



First Series Second Series Third Series

FIGURE 12. HONEYCOMB BULKHEAD PANELS

TABLE 3. PROPERTIES OF THE DIFFERENT BULKHEAD SERIES

Property	Teklam N510 First Series	Teklam N510E Second Series	Teklam Third Series
Honeycomb core	Nomex	Nomex	Aluminum
Face sheets	Phenolic/Fiberglass	Epoxy/Fiberglass	Fiberglass
Thickness (in)	1.0	1.0	1.0
Weight (lb/sq ft)	0.74	0.74	0.74
Facings (in)	0.04	0.04	0.04
Core (in)	1/8	1/8	3/8
Density (lb/ft^3)	3.0	3.0	1.0
Flat wise Compression (psi)	310	275	NA
Carpet	No	Yes	Yes

A carpet typically used in aircraft installations was used to cover both the face sheets. The layup of the bulkhead panels is shown in the figure 13.

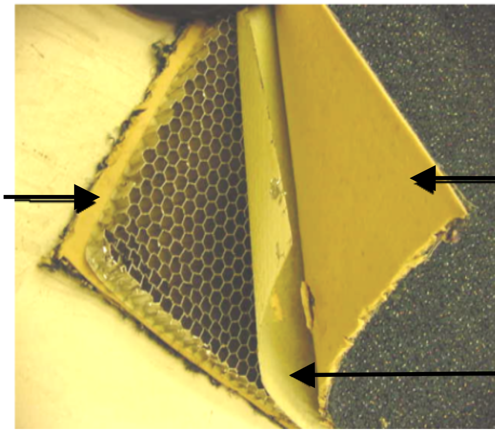
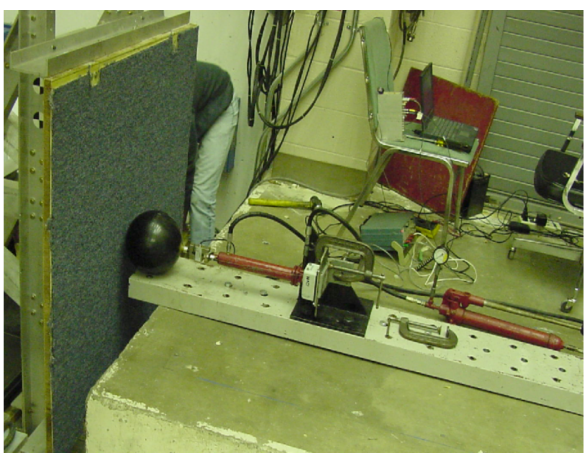
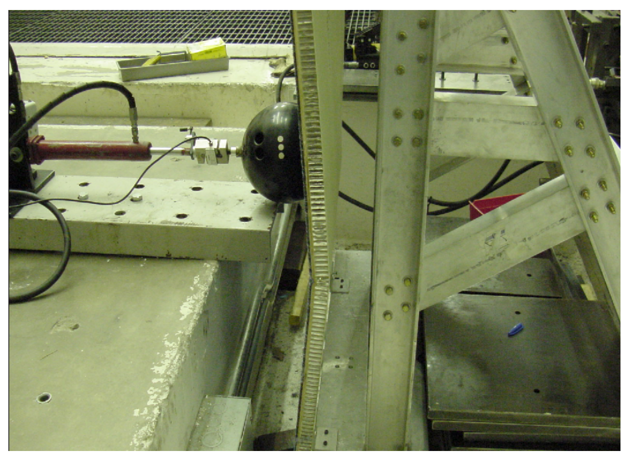


FIGURE 13. BULKHEAD PANEL LAYUP

Three honeycomb bulkhead series were subjected to static testing (figure 14) to evaluate their stiffness values. The test setup is shown in figure 14(a). An actuator assembly with a 16-lb bowling ball attached to one end was used to apply the static load. The load was gradually increased to a maximum applied load of approximately 1200 lbs at which time the bulkhead crushed (figure 14(b)). Figures 15 and 16 show the load deflection characteristics and stiffness values for the three bulkheads. The slope of the loading curve gives the initial stiffness of the bulkhead. The static test results for the bulkhead series are given in table 4.



(a) Test Setup



(b) Bulkhead Deflection (Series III) Under Normal Load

FIGURE 14. STATIC TESTING OF HONEYCOMB BULKHEAD

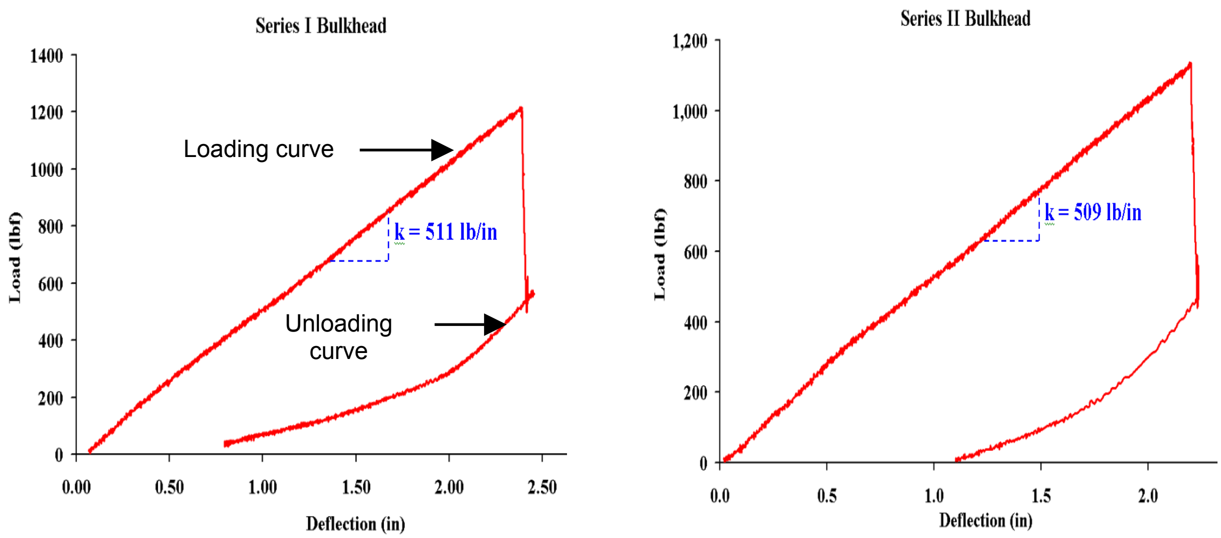


FIGURE 15. LOAD DEFLECTION CHARACTERISTICS AND STIFFNESS VALUES OF SERIES I AND II BULKHEADS

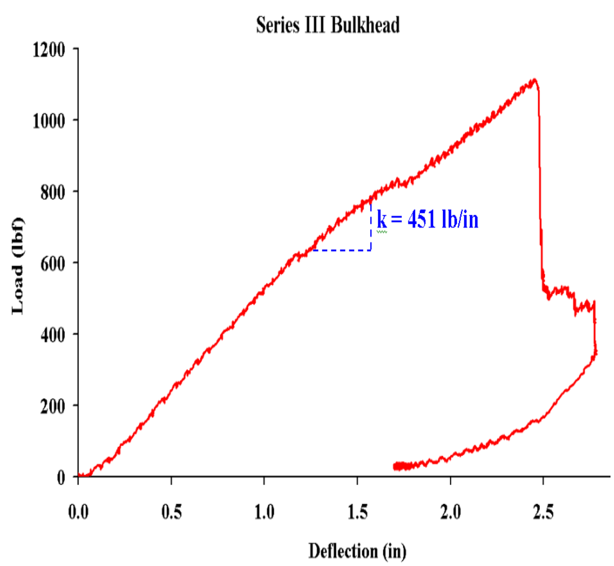


FIGURE 16. LOAD DEFLECTION CHARACTERISTICS AND STIFFNESS VALUE OF SERIES III BULKHEAD

TABLE 4. STATIC TEST RESULTS FOR THE BULKHEAD SERIES

Bulkhead	Series I	Series II	Series III
Maximum Deflection (in)	2.46	2.24	2.79
Maximum Crush Load (lbf)	1217	1137	1115
Stiffness (lb/in)	511	509	452

As observed, the initial stiffness of all the three bulkheads is within a narrow range of about 60 lb/in. Comparing their stiffness values to the design curves, it can be postulated that for a 33-in. seat setback distance, a HIC value over 1000 can be expected for series I and II, and a HIC value less than 1000 can be expected for series III bulkheads. For a 35-in. seat setback distance, all the series appeared to provide a possible solution. The performance of the three bulkheads needs to be assessed by conducting dynamic sled tests.

5. DYNAMIC TESTS OF THE DESIGNED BULKHEADS.

A series of 10 full-scale sled tests were conducted on three different series of bulkheads to determine their performance for HIC compliance.

5.1. DYNAMIC TEST ON A SERIES I BULKHEAD.

One full-scale sled test (01008-3) was conducted on a series I bulkhead to measure the accelerations in the head of the Hybrid II ATD. The test was conducted at a seat setback distance of 35 in. (figure 17). A polyester lap belt was used to restrain the ATD. An iron seat with no seat cushions and a zero degree yaw plate was used to isolate the response of the Hybrid II ATD from the complications that might arise from the structural crash response of a deformable seat.

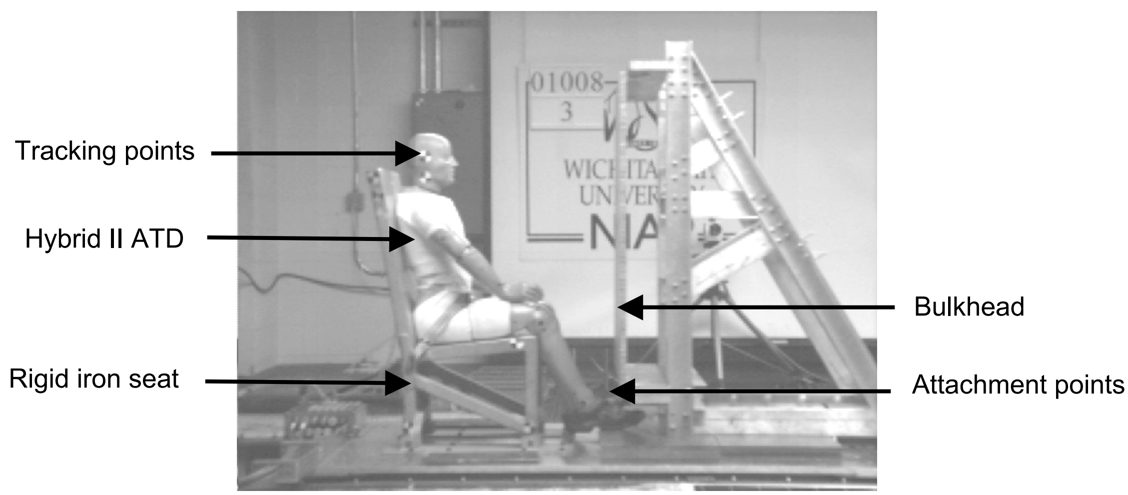


FIGURE 17. SETUP FOR FULL-SCALE SLED TEST 01008-3 ON A SERIES I BULKHEAD

Three optical targets were attached to the seat to establish a moving reference frame. Four additional targets were mounted on the ATD, to track the dummy motion. Triaxial accelerometers were mounted in the ATD head c.g. to record head accelerations. The optical speed trap system was adjusted so that it triggered the high-speed video system just prior to the start of the sled deceleration. The sled deceleration pulse shapes were captured from two longitudinally sensing accelerometers that were mounted on the sled. The ATD kinematics are shown in figure 18. The resultant head c.g. acceleration and HIC calculation are shown in figure 19. Table 5 shows the summary of the test results.

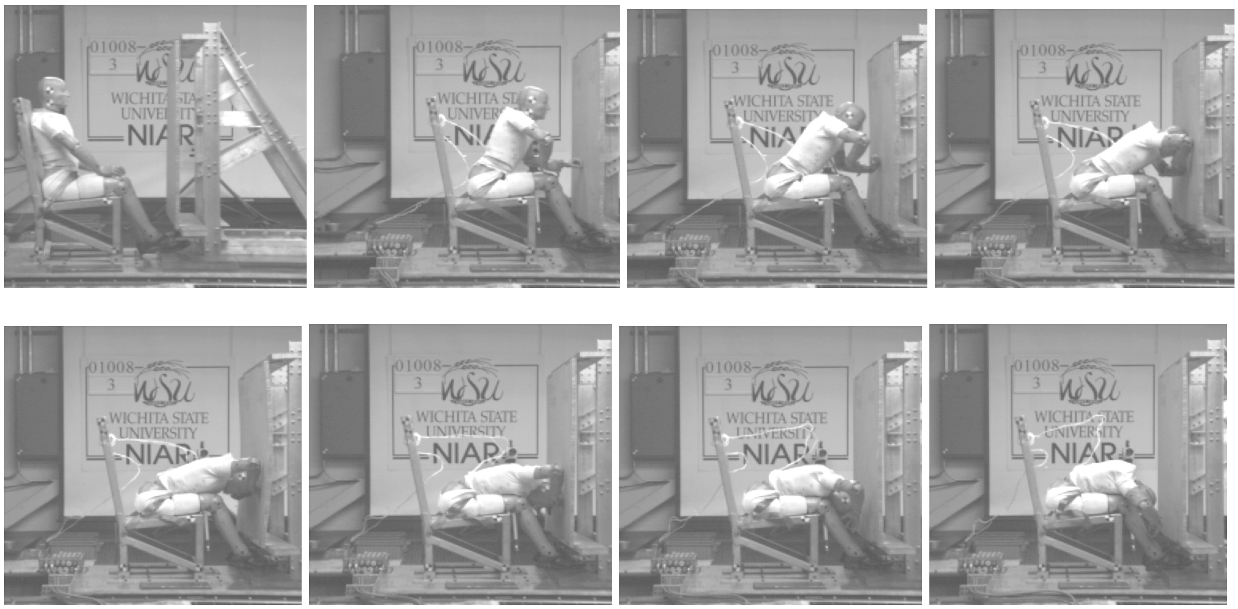


FIGURE 18. ATD KINEMATICS FOR SLED TEST 01008-3

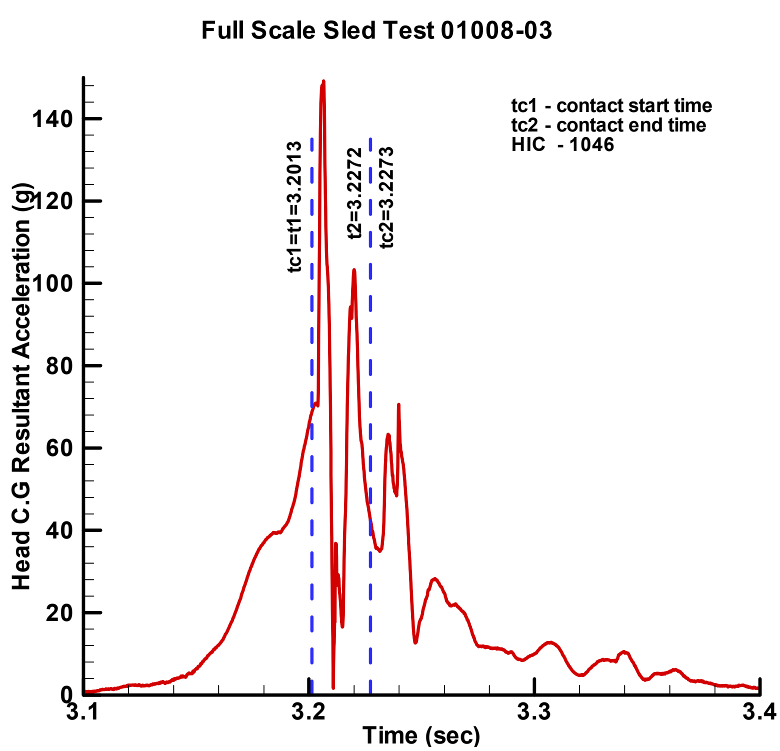


FIGURE 19. RESULTANT HEAD C.G. ACCELERATION AND HIC VALUE FOR A SERIES I BULKHEAD AT 35-in. SEAT SETBACK DISTANCE (TEST 01008-3)

TABLE 5. SUMMARY OF THE TEST RESULT FOR A SERIES I BULKHEAD

Test	Sled Test Acceleration (g)	Seat Setback Distance (in)	Head Peak Acceleration (g)	Average Acceleration (g)	HIC	Δt (ms)	Head Impact Angle (deg)	Head Impact Velocity (ft/s)
01008-3	16.7	35	149.1	82	1046	25.9	57	40

A detailed summary of this test is presented in appendix C. Although the design curves predict a HIC of about 700, the dynamic test produced a higher HIC. Since the series I bulkheads (the stiffest ones) did not produce HIC value less than 1000 for a seat setback distance of 35 in., further tests with these bulkheads at smaller seat setback distances were not conducted.

5.2 DYNAMIC TESTS ON SERIES II BULKHEADS.

A series of five full-scale sled tests were conducted at different seat setback distances. Test 01008-4 was conducted at 35-in. seat setback distance. Tests 01008-6 and -8 were conducted with the same configuration for repeatability. The test setup for test 01008-8 is shown in figure 20. The ATD kinematics for test 01008-8 is shown in figure 21.

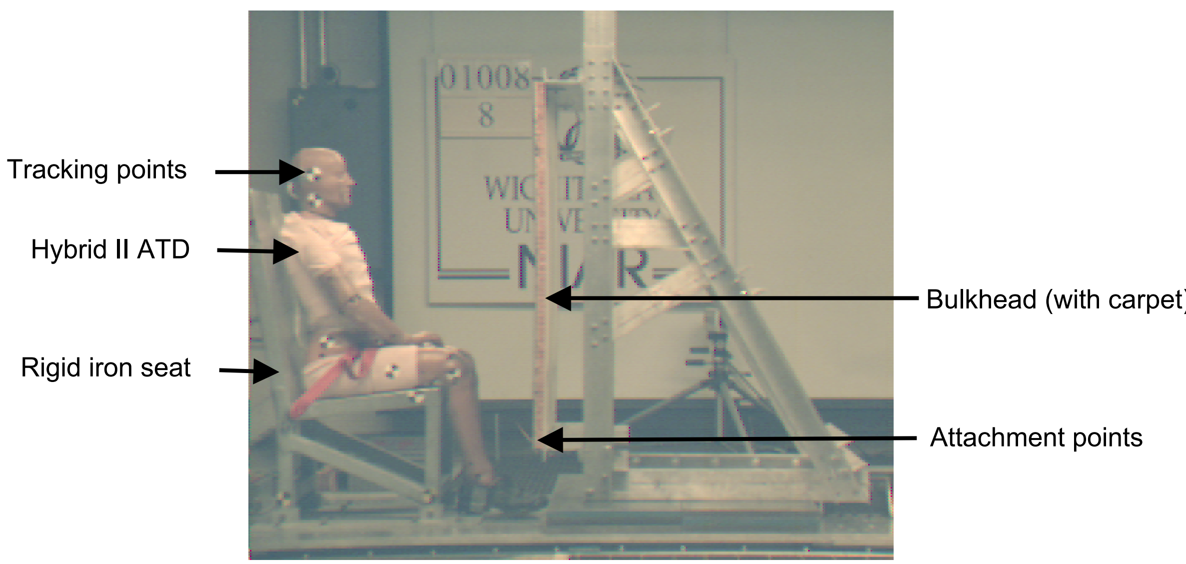


FIGURE 20. SETUP FOR FULL-SCALE SLED TEST 01008-8 ON A SERIES II BULKHEAD

FIGURE 21. ATD KINEMATICS FOR SLED TEST 01008-8

The resultant peak head acceleration for the test was 132 g and the HIC was 783. Figure 22 shows the resultant head c.g. acceleration.

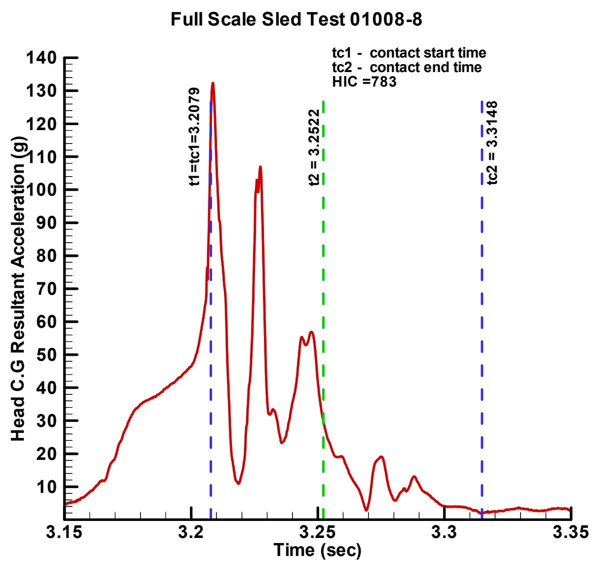


FIGURE 22. RESULTANT HEAD C.G. ACCELERATION AND HIC VALUE FOR A SERIES II BULKHEAD AT 35-in. SEAT SETBACK DISTANCE (TEST 01008-8)

Tests 01008-7 and -9 were conducted at 33-in. seat setback distance. Figure 23 shows the resultant head c.g. acceleration and the HIC value for test 01008-9. Table 6 summarizes the test results obtained on the series II bulkheads. As observed, series II bulkheads failed to produce a HIC of less than 1000 at a 33-in. seat setback distance.

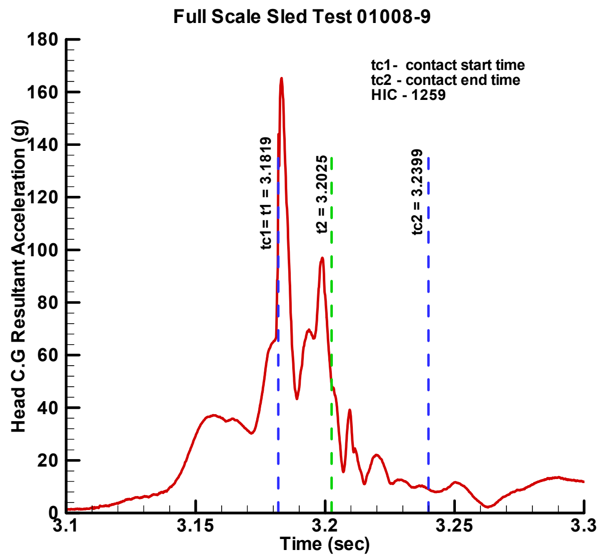


FIGURE 23. RESULTANT HEAD C.G. ACCELERATION AND HIC VALUE FOR A SERIES II BULKHEAD AT 33-in. SEAT SETBACK DISTANCE (TEST 01008-9)

TABLE 6. SUMMARY OF THE TEST RESULTS FOR SERIES II BULKHEADS

Test	Sled Test Acceleration (g)	Seat Setback Distance (in)	Head Peak Acceleration (g)	Average Acceleration (g)	HIC	Δt (ms)	Head Impact Angle (deg)	Head Impact Velocity (ft/s)
01008-4	16.0	35	160	57	617	25.0	56	46
01008-6	15.6	35	139	53	754	36.8	64	41
01008-8	16.0	35	132	50	783	44.3	59	54
01008-7	17.4	33	218	103	1383	12.9	46*	48
01008-9	16.0	33	165	82	1259	20.6	53	43

* High sled pulse resulted in a large seat belt stretch thus lowering the head impact angle.

A detailed summary for each of these tests on the series II bulkheads is presented in appendix C.

5.3 DYNAMIC TESTS ON SERIES III BULKHEADS.

Four full-scale sled tests (tests 01008-13 through -16) were conducted at both 33- and 35-in. seat setback distances. Figure 24 shows the setup for sled test 01008-13 for 33-in. seat setback distance. Figure 25 shows the ATD kinematics.

The HIC value obtained from this test was 623. The head peak and average accelerations were 144 g and 55 g with a HIC window of 27.7 ms. Figure 26 shows the resultant head c.g. acceleration and HIC value.

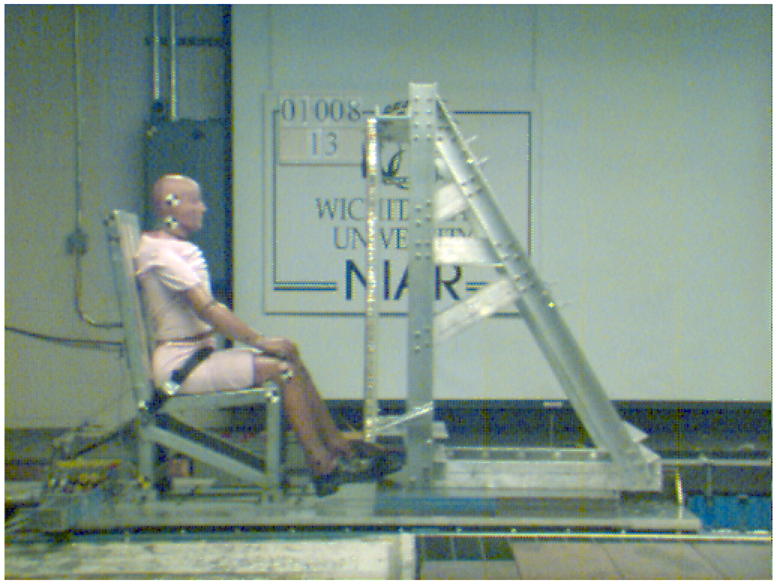


FIGURE 24. SETUP FOR FULL-SCALE SLED TEST 01008-13 ON A SERIES III BULKHEAD AT 33-in. SEAT SETBACK DISTANCE

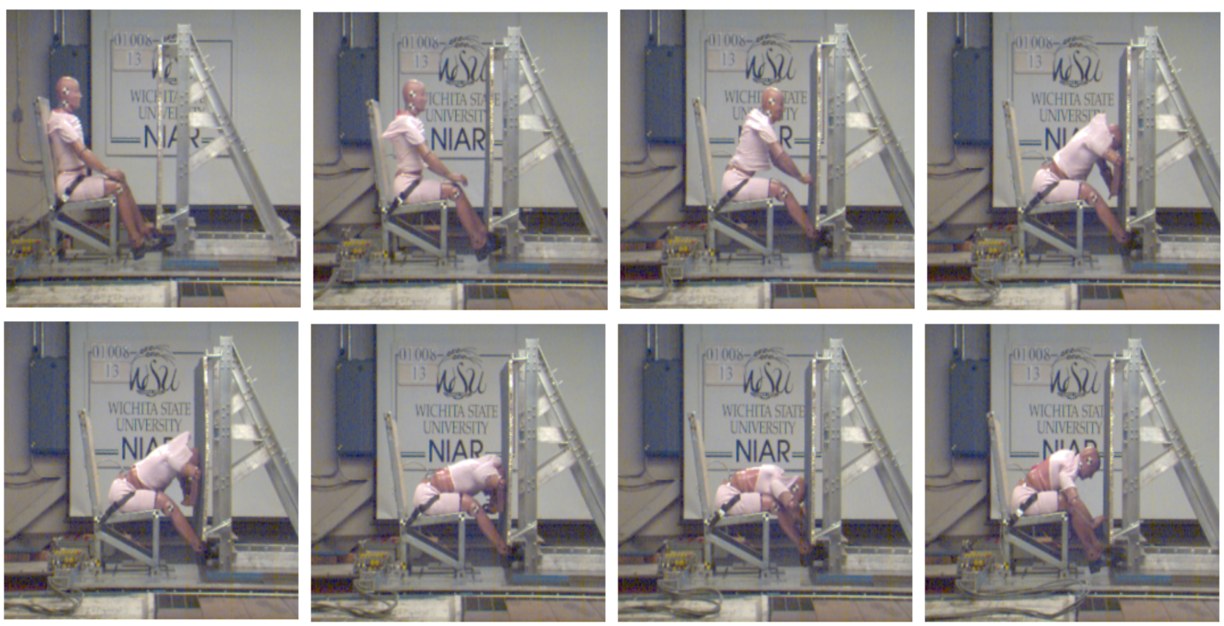


FIGURE 25. ATD KINEMATICS FOR SLED TEST 01008-13

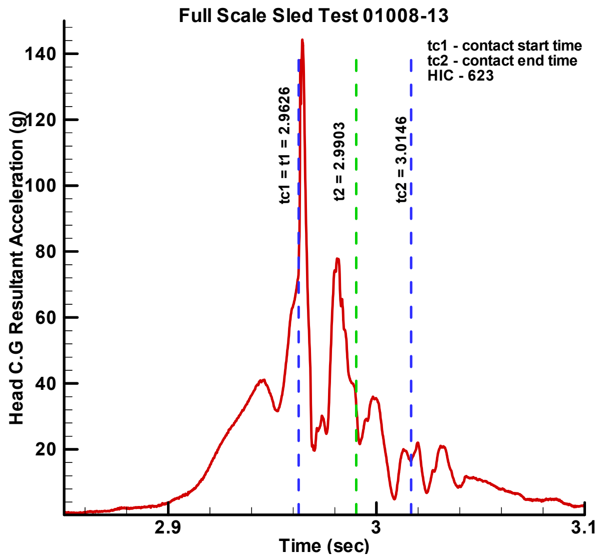


FIGURE 26. RESULTANT HEAD C.G. ACCELERATION AND HIC VALUE FOR A SERIES III BULKHEAD AT 33-in. SEAT SETBACK DISTANCE (TEST 01008-13)

Test 01008-14 was conducted with a seat setback distance of 35 in. The HIC value obtained for this test was 512, which could be attributed to the fact that the ATD head just scraped through the face of the bulkhead. The resultant head peak and average accelerations obtained for this test were 92 g's and 45 g's with a HIC window of 36.8 ms. The resultant head c.g. acceleration and HIC value obtained are shown in figure 27.

Tests 01008-15 and -16 were conducted for repeatability. The test results for the full-scale sled tests on series III bulkheads are given in table 7. A detailed summary for the tests on series III bulkheads is presented in appendix C. Table 8 shows the summary of results from all the full-scale sled test conducted.

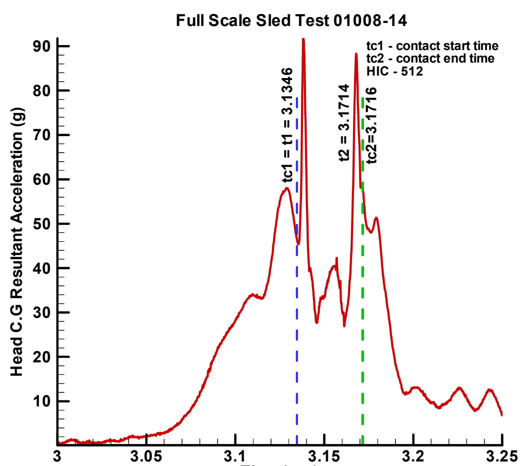


FIGURE 27. RESULTANT HEAD C.G. ACCELERATION AND HIC VALUE FOR A SERIES III BULKHEAD AT 35-in. SEAT SETBACK DISTANCE (TEST 01008-14)

TABLE 7. SUMMARY OF THE TEST RESULTS FOR SERIES III BULKHEADS

Test	Sled Test Acceleration (g)	Seat Setback Distance (in)	Head Peak Acceleration (g)	Average Acceleration (g)	HIC	Δt (ms)	Head Impact Angle (deg)	Head Impact Velocity (ft/s)
01008-13	16.4	33	144	55	623	27.7	55	48
01008-16	16.2	33	134	58	955	37.1	60	46
01008-14*	16.0	35	92	45	512	36.8	69	46
01008-15	16.0	35	103	58	496	23.9	74	53

*The second peak in the acceleration profile is due to the secondary head impact with the femur.

TABLE 8. SUMMARY OF RESULTS FOR TEST SERIES 01008

Test	Material	Seat Setback (in)	Head C.G. Avg Acc (g)	HIC	Δt (ms)	Head Impact Angle (deg)	Head Impact Velocity (ft/sec)
01008-3	Series I[*1]	35	82	1046	26.0	57	40
01008-4	Series II[*2*4]	35	57	617	25.0	56	46
01008-6	Series II[*2 *4]	35	53	754	36.8	64	41
01008-7	Series II[*2 *4]	33	103	1383	12.9	46	48
01008-8	Series II[*2 *4]	35	50	783	44.4	59	54
01008-9	Series II[*2 *4]	33	82	1259	20.6	53	43
01008-13	Series III[*3*4]	33	55	623	27.7	55	48
01008-14	Series III[*3*4]	35	45	512	36.8	69	46
01008-15	Series III[*3*4]	35	58	496	23.8	74	53
01008-16	Series III[*3*4]	33	58	955	37.1	60	46

Note:
[*1] Teklam N510 Phenolic/Nomex Honeycomb panel 1.0″ thick with fiberglass facing on both sides.
[*2] Teklam N510E Epoxy/Nomex Honeycomb panel 1.0″ thick with fiberglass facing on both sides.
[*3] Teklam aluminum panel with fiberglass facing sheets on both sides.
[*4] Carpeted

6. DESIGN METHODOLOGY FOR THE DEVELOPMENT OF HIC-COMPLIANT BULKHEADS.

A flow chart of a methodology developed for the design of a HIC-compliant bulkhead is shown in figure 28. The initial bulkhead design is based on aircraft cabin requirements and previous experience. The stiffness of the bulkhead may be determined by (a) hybrid analytical method, (b) finite element analysis, or (c) static test (see appendix D). The initial stiffness of the bulkhead at the point of head impact is compared with the allowable threshold from the design curves. If the stiffness is below the limiting value of 480 lb/in for 33-in. seat setback and 709 lb/in for 35-in. seat setback distance, the design should meet the HIC requirement. Compliance with the HIC requirement will then be verified by dynamic sled test(s) performed on the bulkheads.

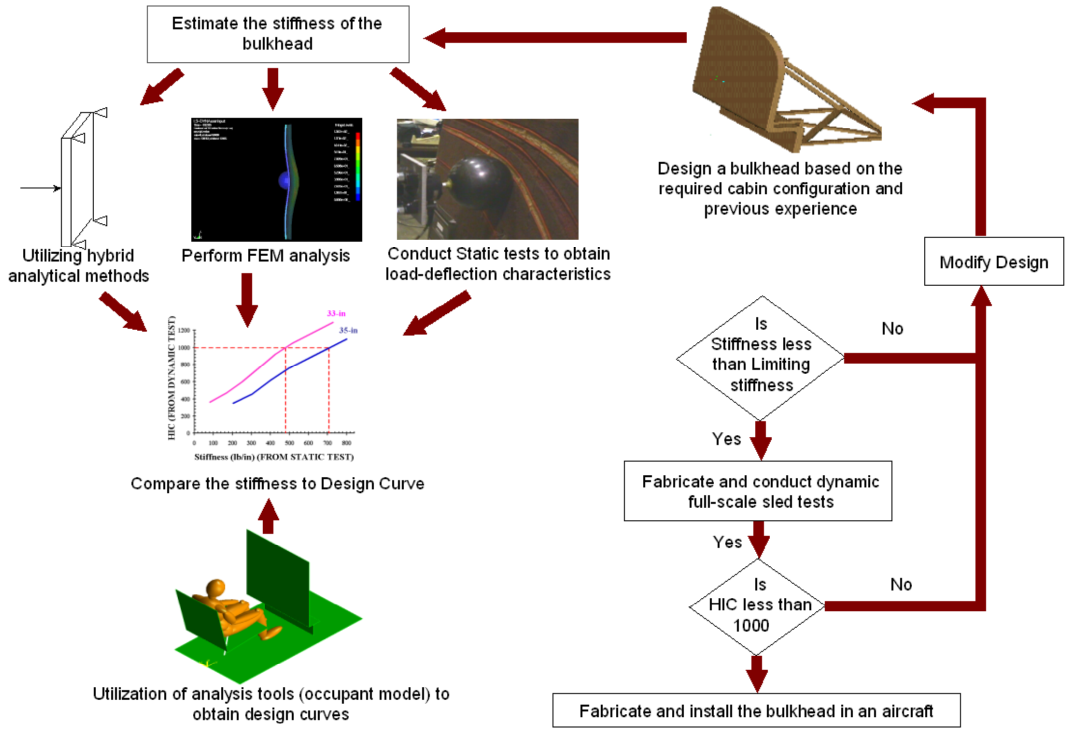


FIGURE 28. DESIGN METHODOLOGY FOR HIC-COMPLIANT BULKHEAD

Aluminum 2024 T3 bulkhead panels (28.5 x 31.0 x 0.063 in.) were used to demonstrate the design methodology. Hybrid finite element analyses and static tests (appendix D) on the aluminum panels resulted in a stiffness of approximately 591 lb/in. Dynamic sled test 96288-004, conducted on the same aluminum 2024 T3 panel, resulted in a HIC of 694. This was plotted against the design curve for a 35-in. seat set back distance (figure 29). Dynamic tests on series III bulkheads at seat setback distances of 33 and 35 in. have also been plotted against the design curve in figure 29. The stiffness of the series III bulkhead is below 480 lb/in, hence, it produces HIC values below the threshold of 1000 for both 35- and 33-in. seat setback distances.

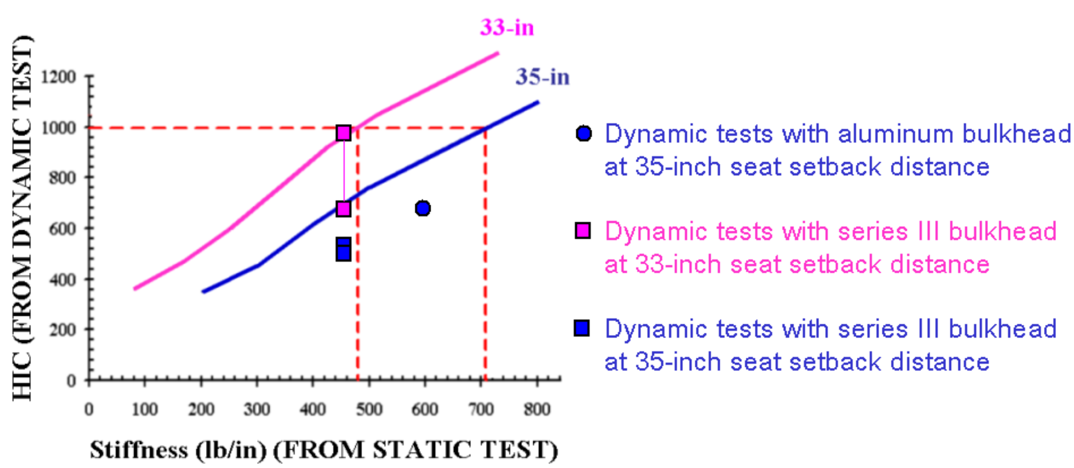


FIGURE 29. STIFFNESS OF THE ALUMINUM PANEL AND BULKHEADS ON THE DESIGN CURVES

It is important to note that the stiffness values for the design curves were developed for a specific head impact location on the bulkhead, for a particular type of seat belt, and for given size and boundary conditions of the bulkhead supporting structure. For the same bulkhead supporting structure, the stiffness could vary at different impact locations.

7. SUMMARY.

Three types of honeycomb bulkhead materials were evaluated for HIC compliance. The bulkheads were subjected to static tests to evaluate their initial stiffness at the head impact location. The bulkheads were then tested dynamically in a full-scale sled test to evaluate the HIC and related head acceleration data. The first bulkhead series failed to meet the HIC requirement. The second bulkhead series met the HIC and related head acceleration requirement at a seat setback distance of 35 in. but failed at 33 in. The third bulkhead series performed well at both 35- and 33-in. seat setback distances.

The study also produced design guidelines for the selection of HIC-compliant bulkhead material. The methodology requires an estimate of the initial stiffness of the bulkhead. The following criteria are recommended for the design of aircraft bulkheads or cabin class divider panels:

a. The initial stiffness of the panel should be less than 480 lb/in for 33-in. seat setback distance (verified by tests).

b. The initial stiffness of the panel should be less than 709 lb/in for 35-in. seat setback distance (not verified by tests).

c. Two to four inches of crush space is required.

8. REFERENCES.

1. 14 CFR Part 23—Airworthiness Standards: Normal, Utility and Acrobatic Category Airplanes, U.S. Government Printing Office, Washington, D.C., revised January 1, 1986.

2. 14 CFR Part 25—Airworthiness Standards: Transport Category Airplanes, U.S. Government Printing Office, Washington, D.C., revised January 1, 1986.

3. Hooper, S.J. and Lankarani, H.M., "Parametric Study of Crashworthy Bulkhead Designs," FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey, DOT/FAA/AR-02/103, October 2002.

4. Ezra, A.A. and Fay, R.J., "Dynamic Response of Structures," Proceedings of a Symposium, Stanford University, CA, June 28 and 29, 1971.

5. Timoshenko, S. and Woinowsky-Krieger, "Theory of Plates and Shells," McGraw-Hill Publications, 1959.

APPENDIX A—DATA ANALYSIS PROCEDURE

When a sled test is conducted, data captured from the accelerometers and video is recorded onto a compact disk. The compact disk will contain the raw data and the filtered data for the acceleration histories. The video data is further analyzed to obtain the position and velocity of various bodies at different stages in the test.

For each test, a summary of the data is represented in the appendices B, C, and E of this report. The following summarizes the procedure.

A.1 ANALYSIS OF VIDEO DATA.

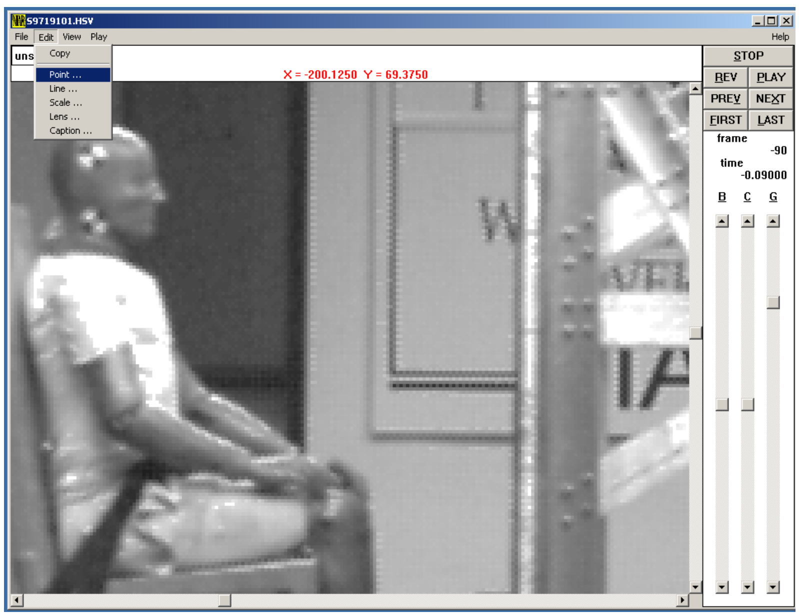
1. Open the movie player 'hsv95.exe'.

2. Open the .hsv (S*******.hsv) from CD containing the sled data from the Impact Dynamic Laboratory.

3. Creating a point

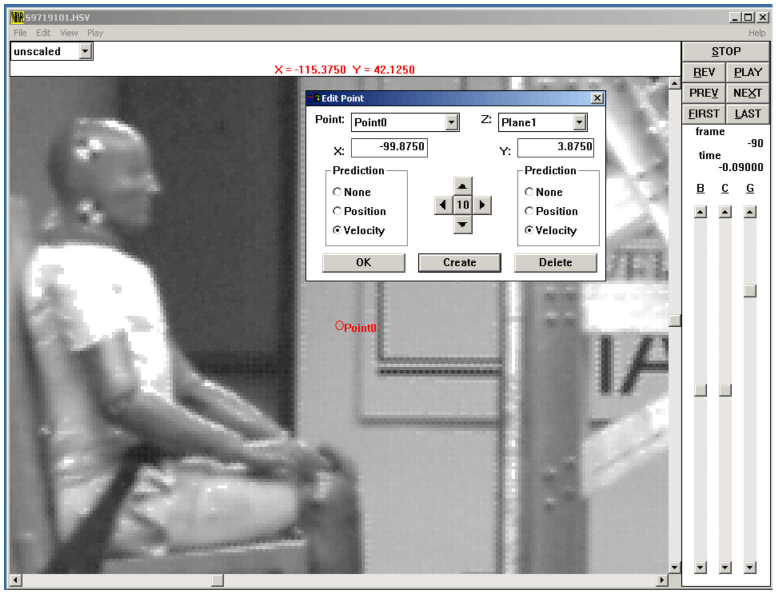
   a. Zoom in appropriately using the 'View' menu.

b. Select ‘Point’ option from the ‘Edit’ menu.



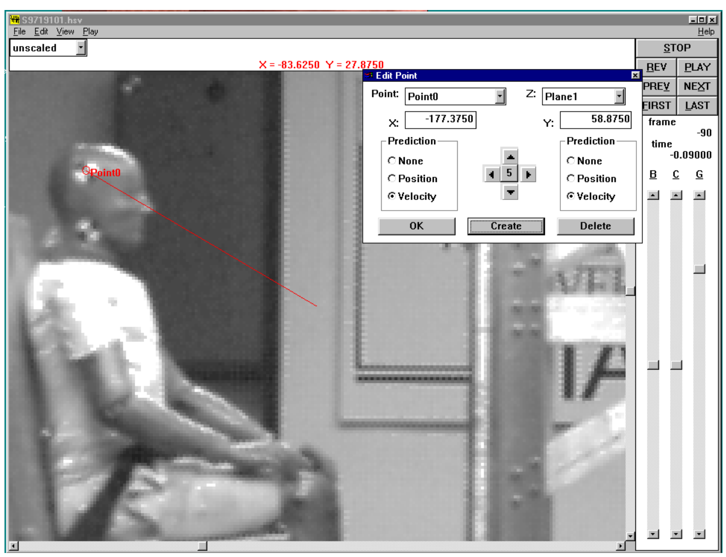
c. Select the velocity option in both X and Y frames from the ‘Edit Point’ window.

d. Click on ‘Create’ to generate the point and keep the window open. (DO NOT CLICK OK, as this will close the window). Now a point is created at the center of the screen.



4. Creating the trajectory

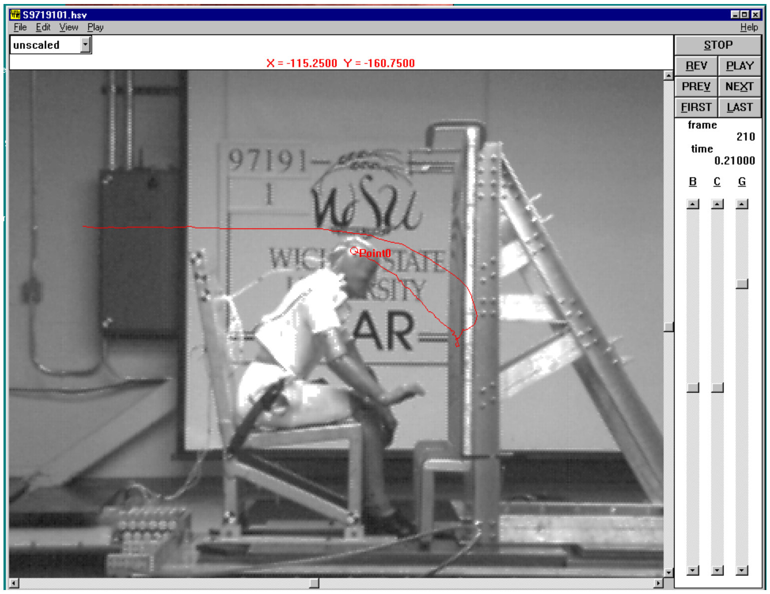
a. Select the center of the target point using the mouse.



b. Go to the next frame → select 'NEXT' button on the screen (shortcut key is CTRL + X) and again select the center of the target point using the mouse (shortcut key for moving the point is ALT + up/down/left/right arrows. This will make the point move by the number of pixel shown at the center of the cross).

c. By doing the above no new points are created, but only the trajectory is being traced.

d. Repeat the above step (b) till the end of the video to generate the complete trajectory.



e. Now click OK on the 'Edit Point' window.

f. Repeat the trajectory tracking procedure for all the points of interest where target points have been placed.

g. Save the file in the appropriate disk location using the 'save as' option from the 'File' menu.

h. **filename.hsd** will be created.

i. Save a copy of the **S*******.hsv** file also in the same location.

j. Open the file ‘filename.hsd’ using the ‘hsv95.exe’ program.

k. The file with all the trajectories will be displayed.

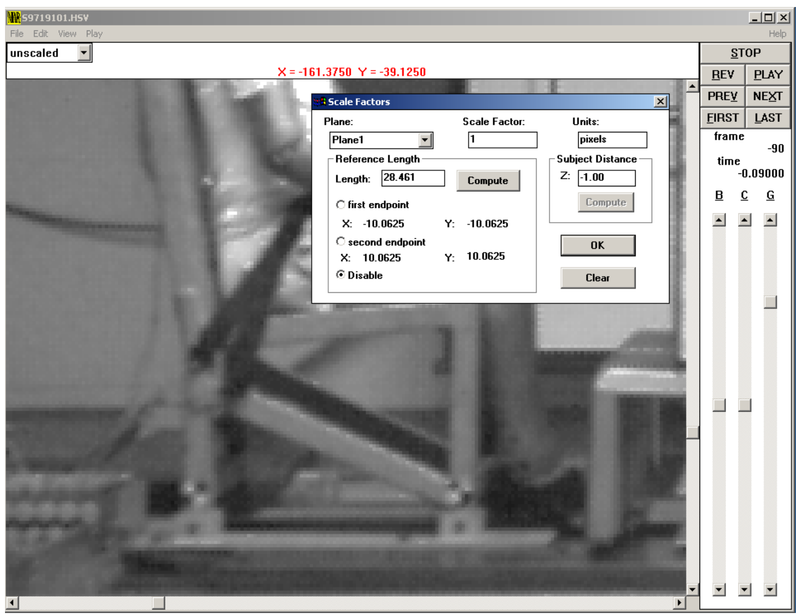
l. The scale factor for the video is to be determined.

5. Measuring the scale for the measurement of position and velocity from video data

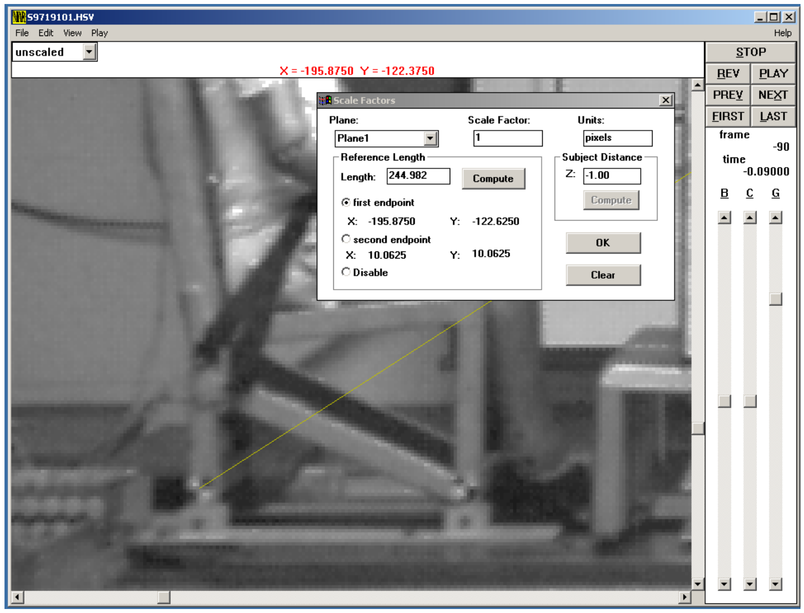
   a. Zoom in appropriately using the ‘View’ menu.

   b. Zoom into the region where tracking points have been pasted and the distance between them is known.

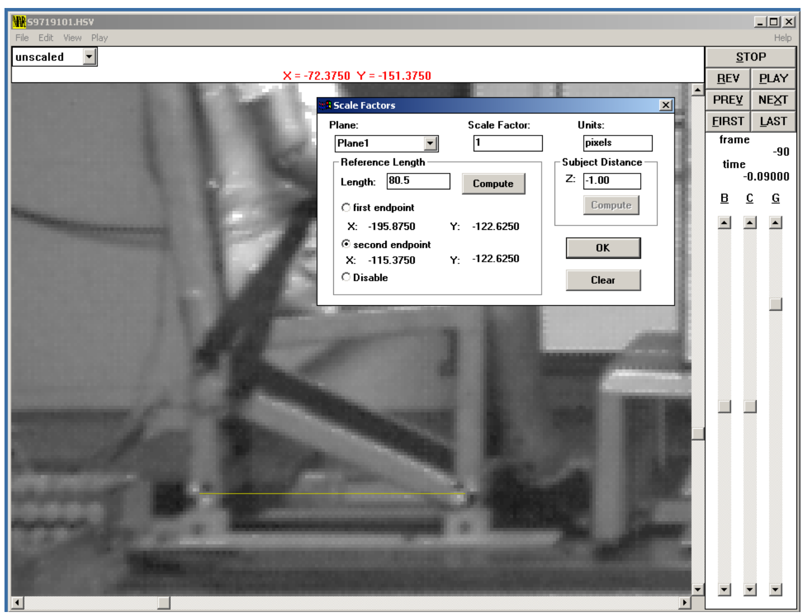
   c. Select the ‘Scale’ option from the ‘Edit’ menu from the ‘Scale Factor’ window to open.



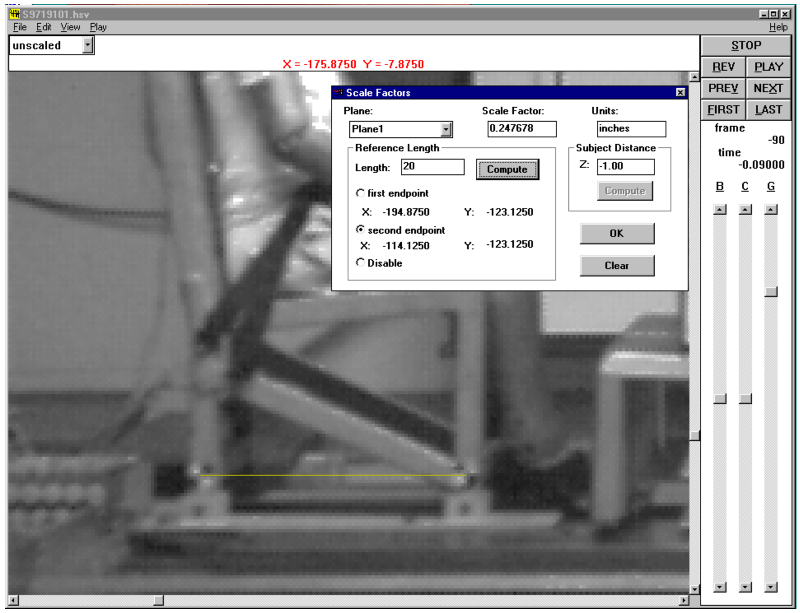
d. Select the ‘first end point’ option and then click on the first target point.



e. Select the ‘second end point’ and then click on the second target point.



f. Type in the distance between the two target points in the ‘Length’ textbox and correct the units appropriately. Then click ‘compute’ to arrive at the scale factor.



6. Obtaining data for velocity and angle calculation

   a. Once the scale factor is calculated, then export the model to the appropriate disk location. Select the option 'Export' from 'File' menu.

   b. **filename.csv** will be created.

   c. This file can be opened in MS Excel for further Head impact velocity and angle calculations and also for determining the displacement and velocity of the points that were tracked.

A.2 CALCULATION OF VARIOUS PARAMETERS FROM THE TEST DATA.

1. Sled Deceleration Profile

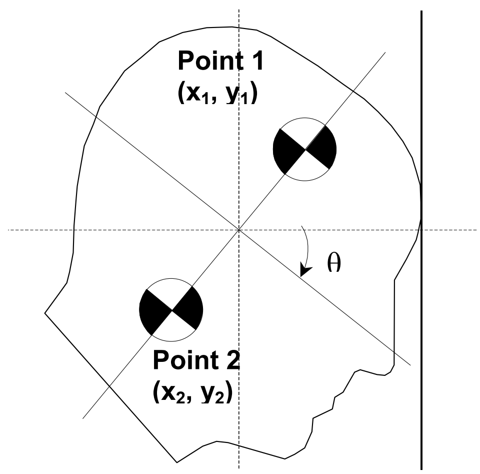
For each test, the sled deceleration data, obtained from the Impact Dynamics Laboratory at NIAR, is plotted against time. The graph is plotted and only shows the portion during the deceleration of the sled. This is done to obtain a clear picture of the pulse shape used in the particular test.

2. Head c.g. Acceleration Time History

The head c.g. acceleration data is obtained from the tri-axis accelerometer placed at the c.g. of the ATD head. From this, the acceleration time histories in x, y, z, and the resultant are obtained. Note that the component in y is negligible as all the sled tests were conducted with no yaw.

3. Head Velocity at the instant of Head Contact

The head velocity is obtained from the video data (filename.csv). The paths of two target points on the head, one on top and one on bottom, of the ATD are tracked. From the video data, captured by the high-speed video camera, the velocities of these target points for each frame is calculated. The velocities are calculated from the target point positions using the central difference method. The average position of the two points is used as the position of the head c.g. The resolution of the video data is 2 ms. The velocity at the contact start time and one step prior to it are calculated. The head impact velocity is taken as the average of the two velocities calculated at these two time steps.



$$X = \frac{x_1 + x_2}{2} \qquad Y = \frac{y_1 + y_2}{2}$$

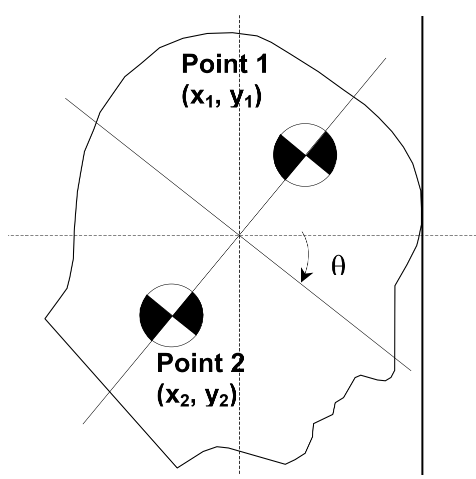
$$V_x = \frac{X_{(t+\Delta t)} - X_{(t-\Delta t)}}{2\Delta t}$$

$$V_y = \frac{Y_{(t+\Delta t)} - Y_{(t-\Delta t)}}{2\Delta t}$$

$$V = \sqrt{Vx^2 + Vy^2}$$

4. Head Impact Angle

The head impact angle is calculated using the video data. The slope of the line joining the two target points on the ATD head is calculated. From the slope, the head impact angle is calculated.



$$\theta = \frac{\pi}{2} - \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \text{ Radians}$$

5. Contact Time

The instants of initial head contact and also departure are noted from the video data. The video time zero is correlated to the actual sled time based on the data obtained from the Impact Dynamics Lab. This is done by correlating the video time zero, which is triggered manually and the time of triggering.

From this the contact start time and end time are obtained by adding the time obtained from the video with the video time zero.

$$t_{c1} = t_{0v} + t_{vc1}$$
$$t_{c2} = t_{0v} + t_{vc2}$$

where

t_{c1} Contact start time
t_{0v} Video time zero
t_{vc1} Contact start time from video
t_{vc2} Contact end time from video
t_{c2} Contact end time

6. HIC

According to the CFR's, the HIC is calculated for the duration of the head contact only, not the entire head acceleration profile. Note that HIC is quite sensitive to small variations in the window size.

7. Head c.g. Average Acceleration

The head c.g. average acceleration is calculated between the t_1 and t_2, the time history ranges over which the maximization of HIC occurs. Average acceleration is calculated, using the 'trapezoidal rule', from the formula given below

$$Avg.Accl = \frac{\sum_{t_1}^{t_2} \frac{\Delta t}{2}(A_t + A_{t+\Delta t})}{(t_2 - t_1)}$$

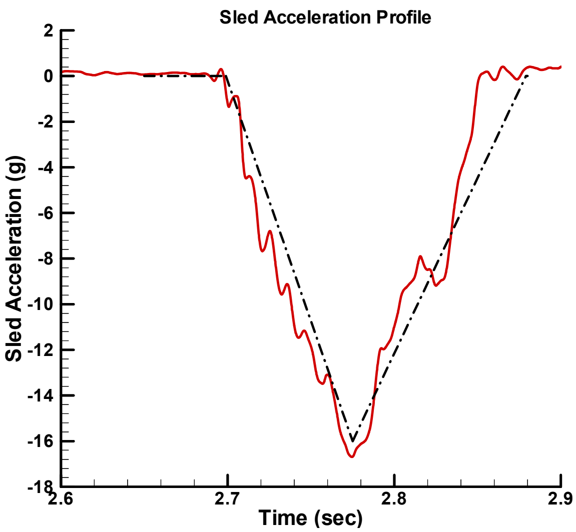
where

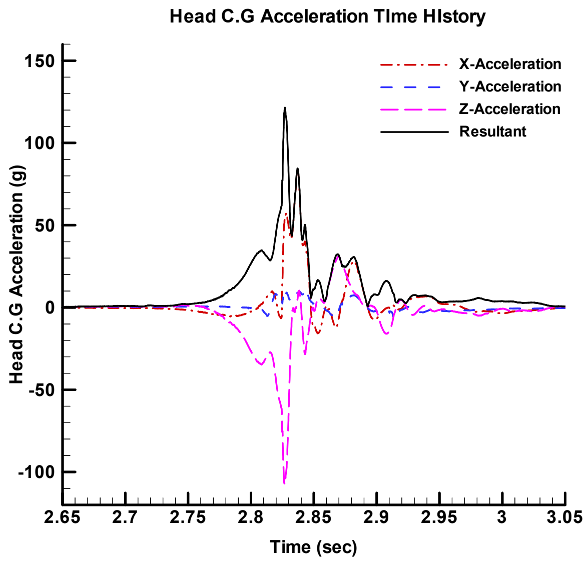
t_1 & t_2 time history over which maximization of HIC occurs
Δt time interval between the two successive set of acceleration data
A_t Acceleration at time 't'
$A_{t+\Delta t}$ Acceleration at time 't + Δt'

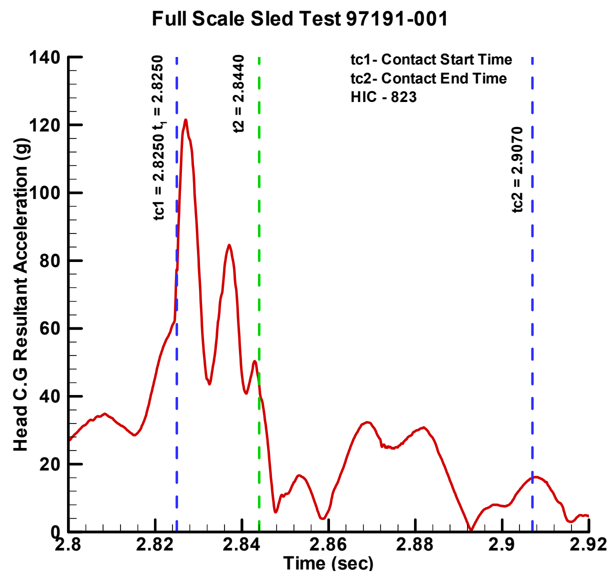
Note: If one of the tracking points becomes difficult to locate for a long period of time, due to obstruction by the clothing of the ATD (or for any other reason), the velocity at the time of impact is calculated using the one visible point. The head impact angles are the resultant angle of the x and y components.

APPENDIX B—DATA SHEETS FOR SLED TESTS 97191-001 AND 97191-002

SLED TESTS 97191-001



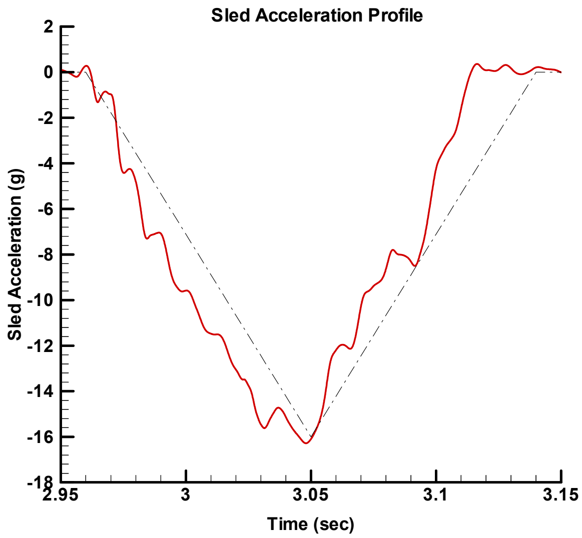


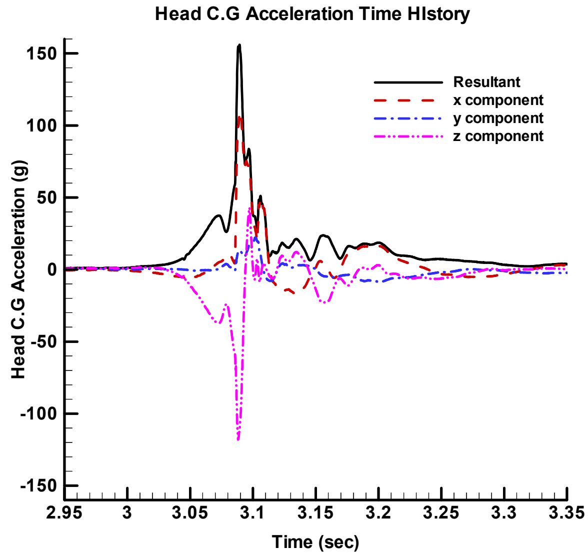


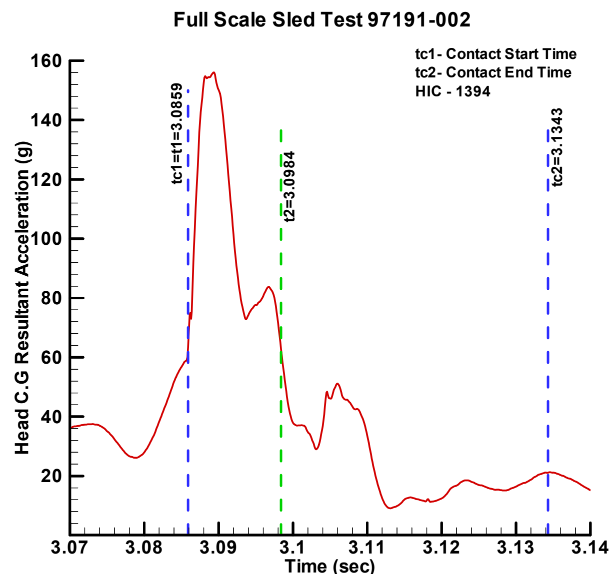
<u>Results of Sled Test 97191-001</u>

Panel	-	Cabin class divider panel
Seat Set back	-	35 in. (88.9 cm)
Peak Sled Deceleration	-	16.7 g
Rise Time	-	73.3 ms
Velocity Change (during rise time)	-	31 ft/s (9.30 m/s)
Velocity Change Total	-	46 ft/s (13.96 m/s)
Head C.G. peak Acceleration	-	121.5 g
$\Delta t = t_2 - t_1$	-	19.0 ms
HIC	-	**823**
Head Impact Velocity	-	45 ft/s (13.68 m/s)
Head Impact Angle	-	53 degree

SLED TEST 97191-002





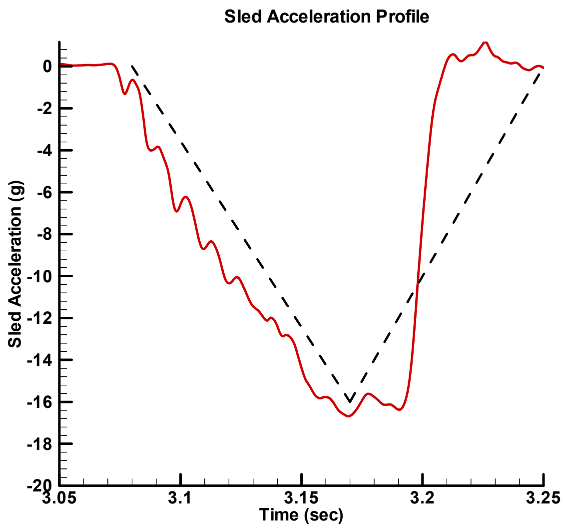


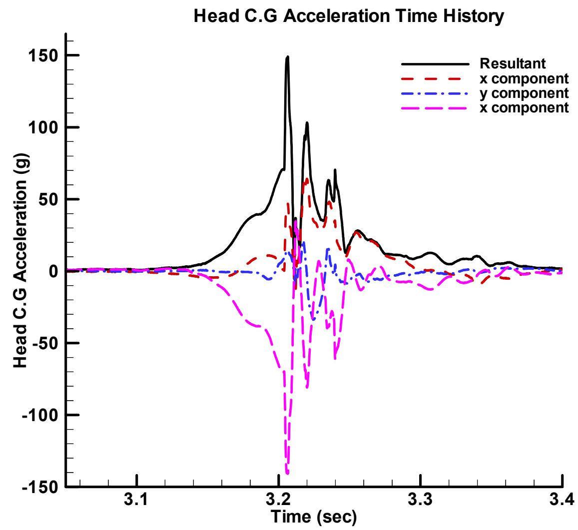
<u>Results of Sled Test 97191-002</u>

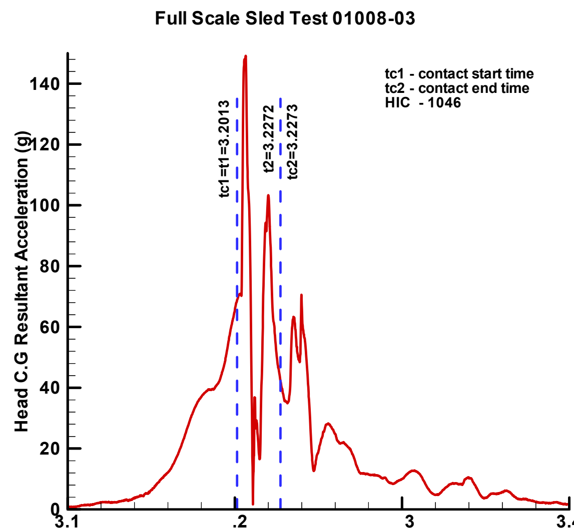
Panel	-	Cabin class divider panel
Seat Set back	-	34 in. (86.36 cm)
Peak Sled Deceleration	-	16.3 g
Rise Time	-	69.8 ms
Velocity Change (during rise time)	-	30 ft/s (9.27 m/s)
Velocity Change Total	-	45 ft/s (13.85 m/s)
Head C.G. peak Acceleration	-	156 g
$\Delta t = t_2 - t_1$	-	12.5 ms
HIC	-	**1394**
Head Impact Velocity	-	45 ft/s (13.82 m/s)
Head Impact Angle	-	42 degrees

APPENDIX C—DATA SHEETS FOR SLED TEST SERIES 01008

SLED TEST 01008-03



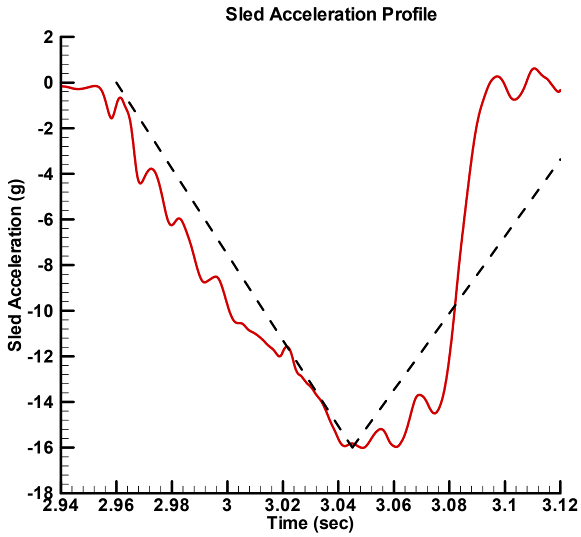


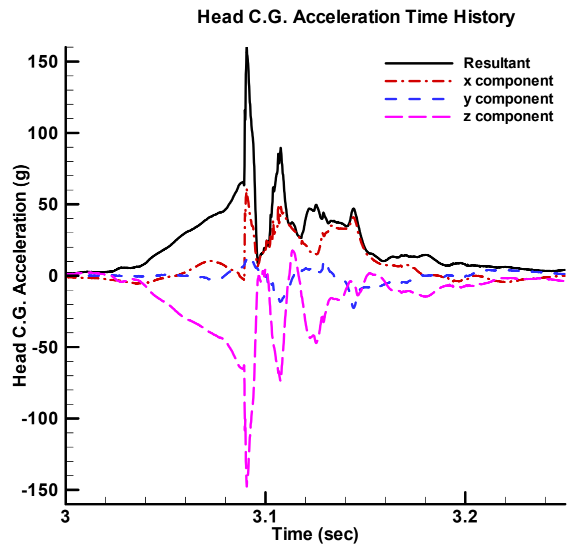


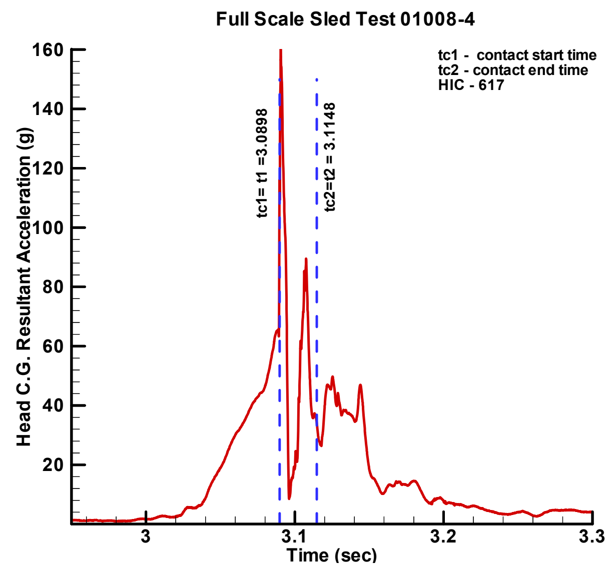
Results of Sled test 01008-3

Panel	-	TEKLAM N510 - Nomex Honeycomb panel 1 in. (2.54 cm) thick with Phenolic/7781fiberglass face sheets
Seat setback distance	-	35 in. (88.9 cm)
Peak sled deceleration	-	16.7 g
Rise time	-	87.8 ms
Velocity change during rise time	-	27 ft/s (8.44 m/s)
Total Velocity change	-	45 ft/s (13.74 m/s)
Head C.G. Peak Acceleration	-	149.1 g
Δt = t2-t1	-	25.9 ms
HIC	-	**1046**
Head average acceleration	-	82 g
Head impact velocity	-	40 ft/sec
Head impact angle	-	57 degrees

SLED TEST 01008-4



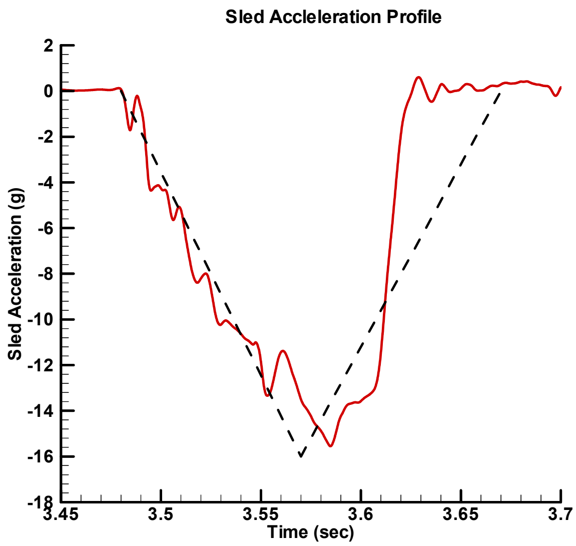


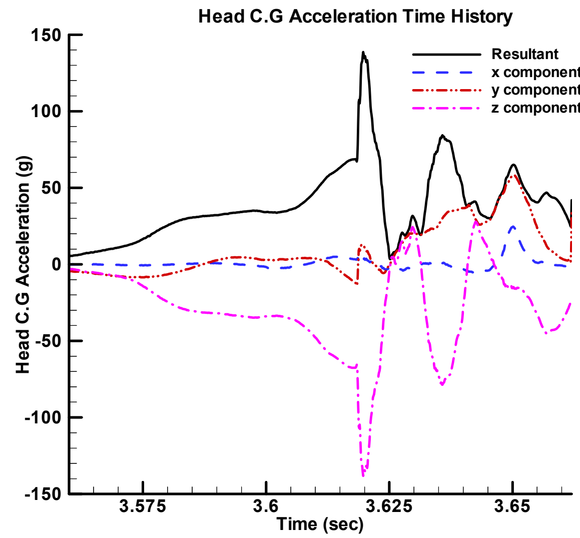


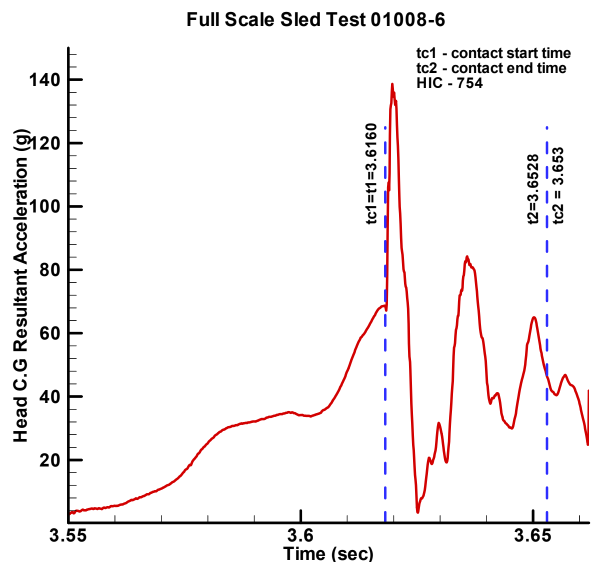
<u>Results of Sled test 01008-004</u>

Panel	-	TEKLAM N510 (E) - Nomex Honeycomb panel 1 in. (2.54 cm) thick with Epoxy/7781 fiberglass face sheets
Seat setback	-	35 in. (88.9 cm)
Peak Sled deceleration	-	16.0 g
Rise time	-	92.2 ms
Velocity change during rise time	-	26 ft/s (8.0 m/s)
Total velocity change	-	45 ft/s (13.6 m/s)
Head C.G. Peak Acceleration	-	160.1 g
Δt = t2-t1	-	25.0 ms
HIC	-	**617**
Head average acceleration	-	57 g
Head Impact velocity	-	46 ft/sec
Head impact angle	-	56 degrees

SLED TEST 01008-6



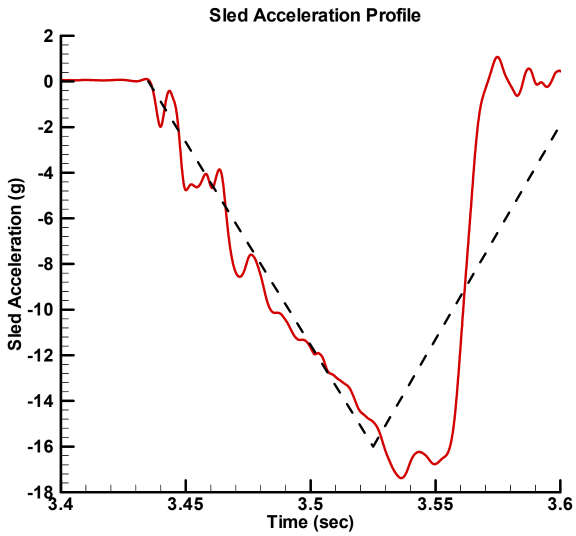


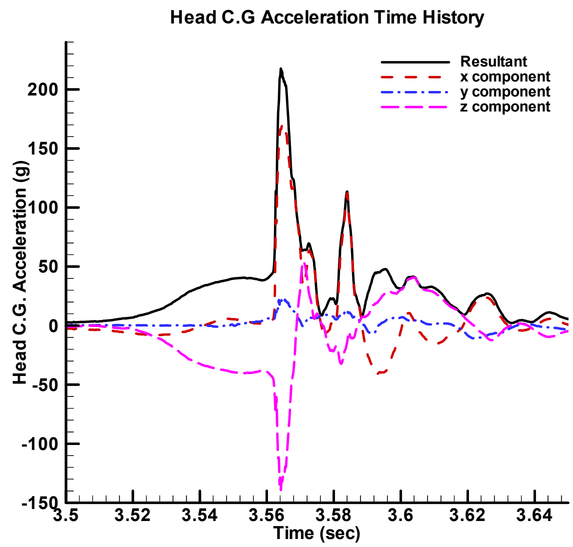


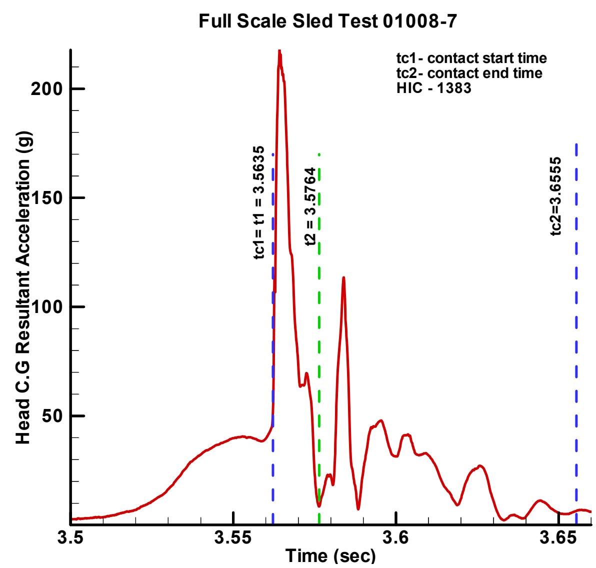
<u>Results of sled test 01008-6</u>

Panel	-	TEKLAM N510(E) - Nomex Honeycomb panel 1 in. (2.54 cm) thick with Epoxy/7781 fiberglass face sheets without carpet.
Seat setback	-	35 in. (88.9cm)
Peak sled deceleration	-	15.6 g
Rise time	-	103.5 ms
Velocity change during rise time	-	23 ft/s (7.2 m/s)
Total velocity change	-	43 ft/s (13.2 m/s)
Head C.G. peak acceleration	-	138.6 g
$\Delta t = t2-t1$	-	36.8 ms
HIC	-	**754**
Head average acceleration	-	53 g
Head Impact velocity	-	41 ft/sec
Head impact angle	-	64 degrees

SLED TEST 01008-7





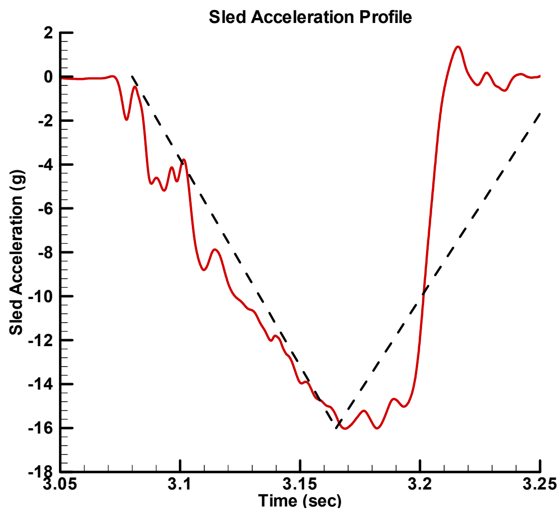


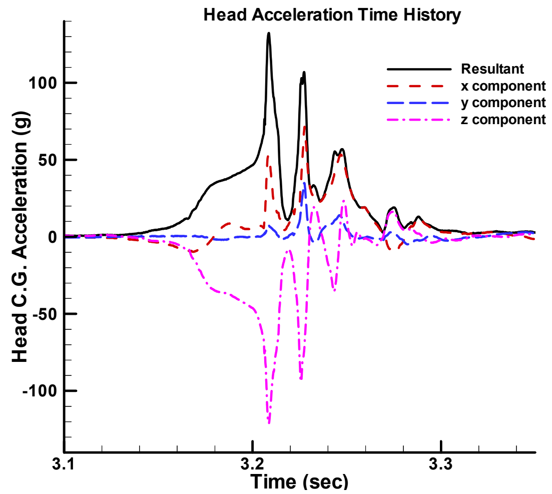
Results of Sled test 01008-7

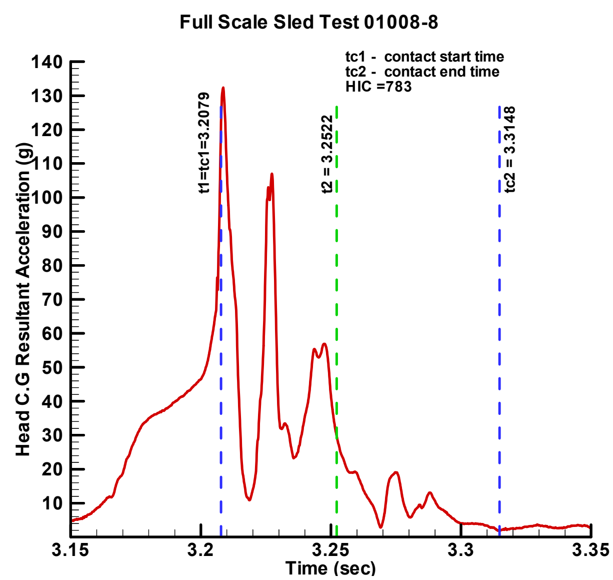
Panel	-	TEKLAM N510(E) - Nomex Honeycomb panel with Epoxy/7781 fiberglass facing sheets 1 in. (2.54 cm) with carpet on both sides
Seat setback	-	33 in. (83.82 cm)
Peak sled deceleration	-	17.4 g
Rise time	-	92.9 ms
Velocity change (during rise time)	-	25 ft/s (7.4 m/s)
Total velocity change	-	44 ft/s (13.6 m/s)
Head C.G. Peak Acceleration	-	217.7 g's
Δt = t2-t1	-	12.9 ms
HIC	-	**1383**
Head average acceleration	-	103 g
Head impact velocity	-	48 ft/sec
Head impact angle	-	46 degrees

* Same as Test 01008-06 configuration but done with carpet on both sides.

SLED TEST 01008-8





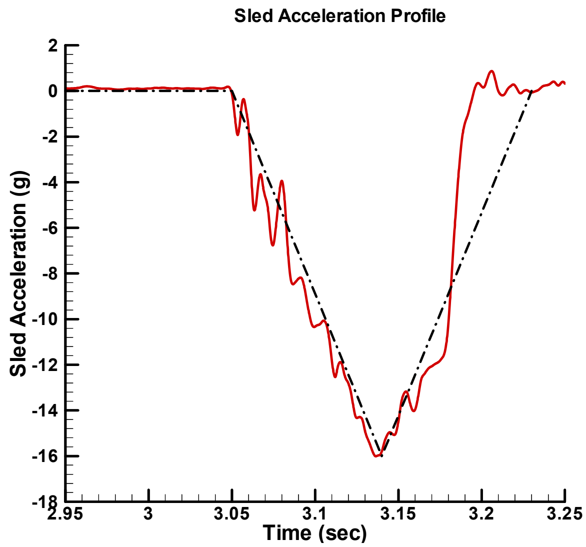


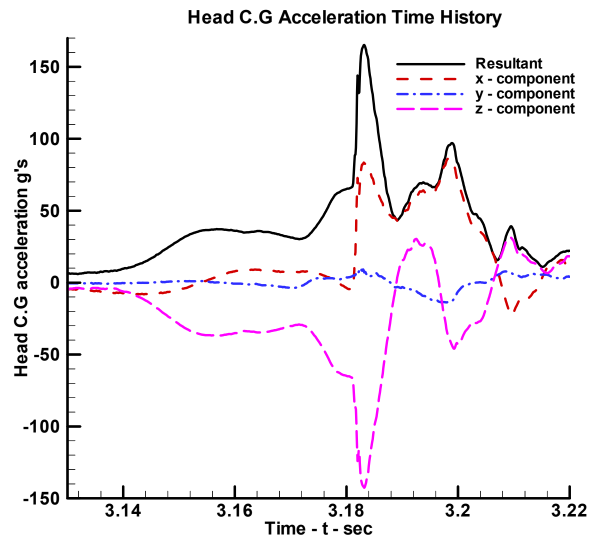
<u>Results of sled test 01008-8</u>

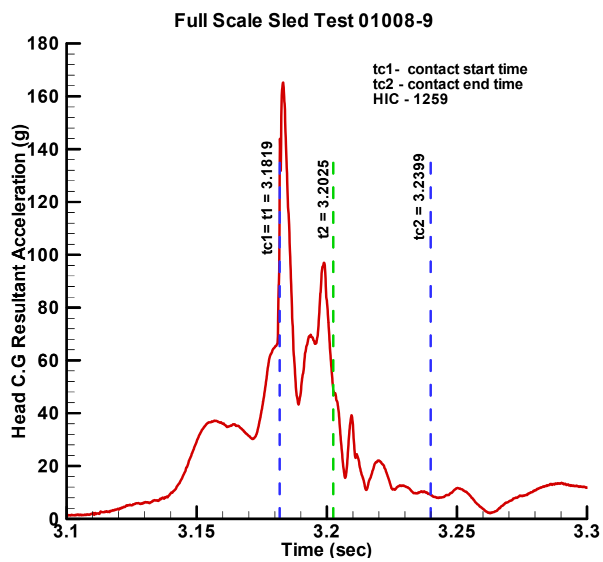
Panel	-	TEKLAM N510(E) - Nomex Honeycomb panel 1 in. (2.54 cm) thick with Epoxy/7781 fiberglass face sheets and carpet typically used in aircraft installations
Seat setback	-	35 in. (88.9cm)
Peak sled deceleration	-	16.0 g
Rise time	-	92.7 ms
Velocity change (during rise time)	-	25 ft/s (7.7 m/s)
Total velocity change	-	44 ft/s (13.4 m/s)
Head C.G. peak acceleration	-	132.4 g
Δt = t2-t1	-	44.4 ms
HIC	-	**783**
Average Accelerations	-	50 g
Head Impact Velocity	-	54 ft/s
Head Impact Angle	-	59 degrees

*Same as Test 01008-06 configuration but with carpet on both sides, done for repeatability

SLED TEST 01008-9



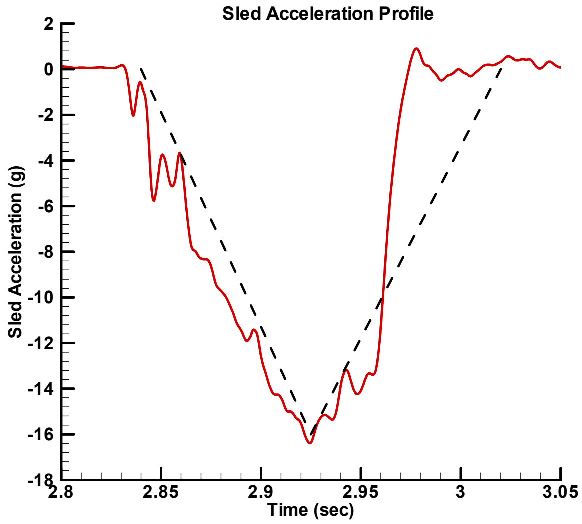


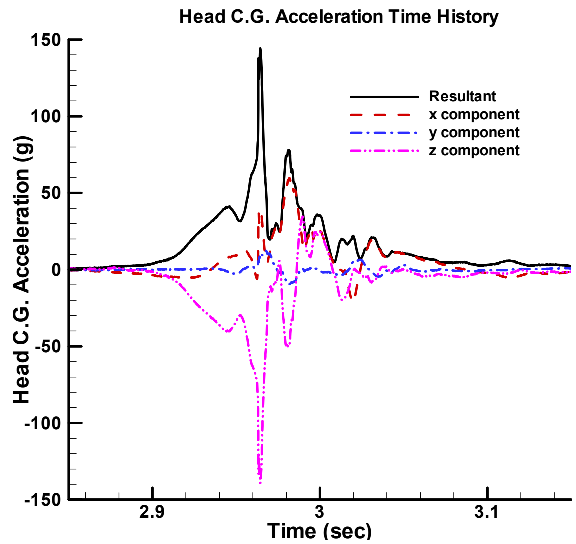


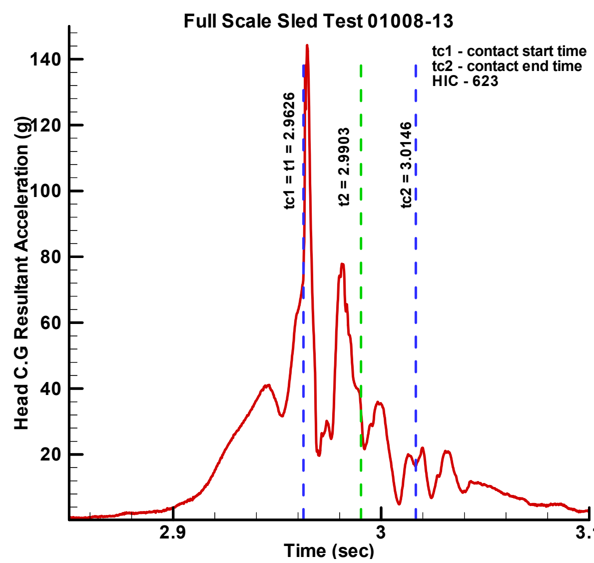
<u>Results of Sled test 01008-9</u>

Panel	-	TEKLAM N510(E) - Nomex Honeycomb panel with Epoxy/7781 fiberglass facing sheets 1 in. (2.54 cm)
Seat setback	-	33 in. (83.82 cm)
Peak sled deceleration	-	16.0 g
Rise time	-	84.6 ms
Velocity change (during rise time)	-	26 ft/s (8.0 m/s)
Total velocity change	-	44 ft/s (13.5 m/s)
Head C.G. Peak Acceleration	-	165.2 g's
Δt = t2-t1	-	20.6 ms
HIC	-	**1259**
Head average acceleration	-	82 g
Head impact velocity	-	43 ft/sec
Head impact angle	-	53 degrees

SLED TEST 01008-13



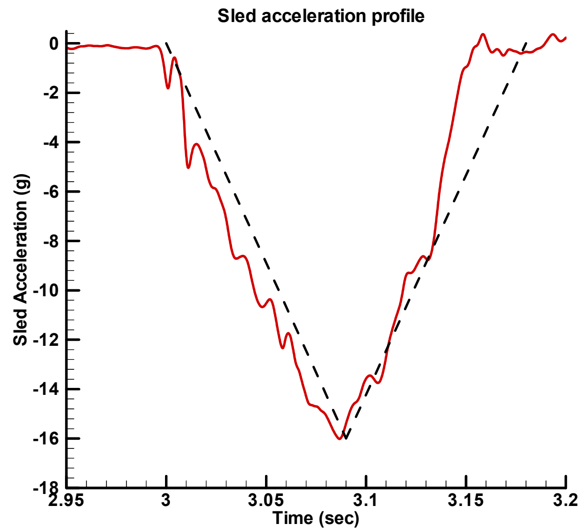


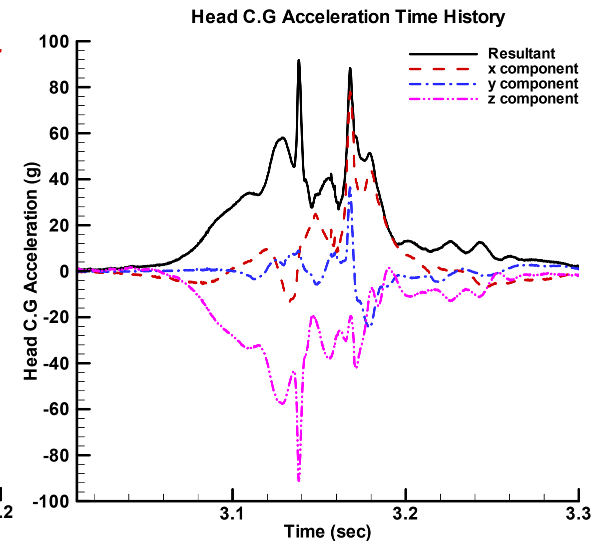


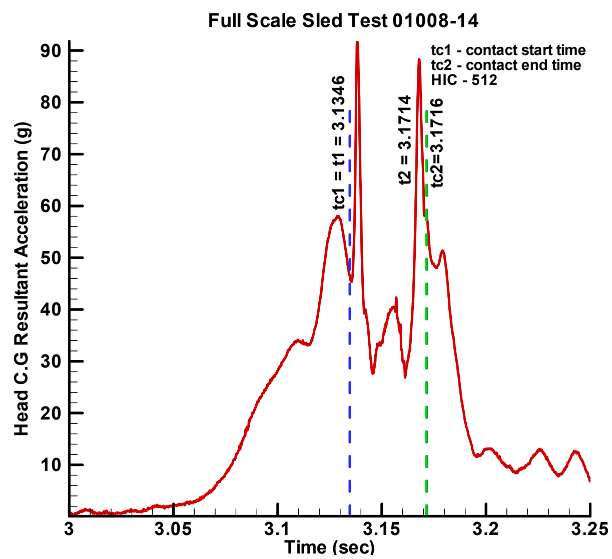
Results of Sled test 01008-13

Panel	-	TEKLAM – Aluminum honeycomb panel with fiberglass facing sheets 1 in. (2.54 cm)
Seat setback	-	33 in. (88.9 cm)
Peak sled deceleration	-	16.4 g
Rise time	-	87.9 ms
Velocity change (during rise time)	-	26 ft/s (8.0 m/s)
Total velocity change	-	45 ft/s (13.7 m/s)
Head C.G. Peak Acceleration	-	144.2 g
Δt = t2-t1	-	27.7 ms
HIC	-	**623**
Head average acceleration	-	55 g
Head impact velocity	-	48 ft/sec
Head impact angle	-	55 degrees

SLED TEST 01008-14



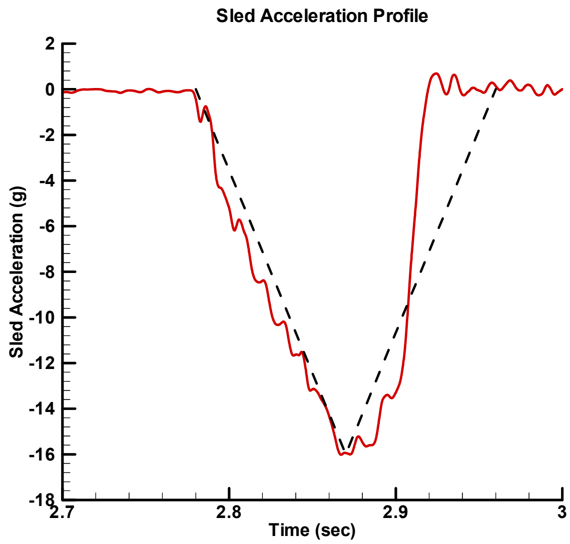


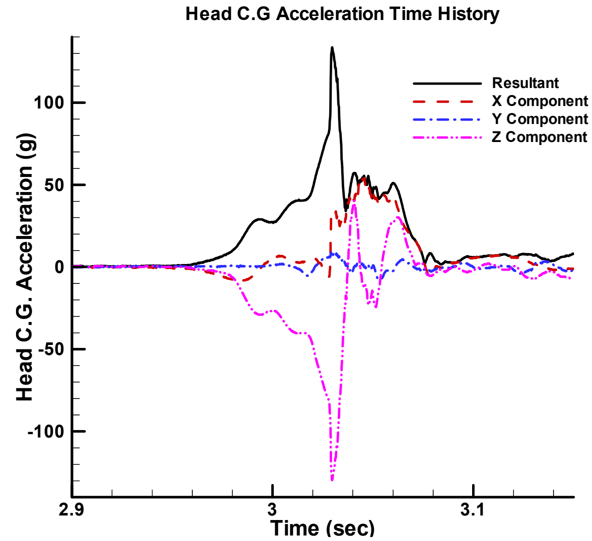


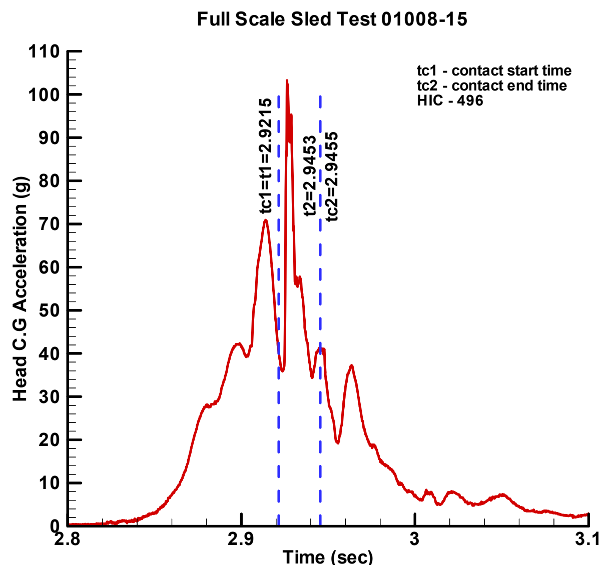
Results of Sled test 01008-14

Panel	-	TEKLAM - Aluminum honeycomb panel with fiberglass facing sheets 1 in. (2.54 cm)
Seat setback	-	35 in. (88.9 cm)
Peak sled deceleration	-	16.0 g
Rise time	-	86.5 ms
Velocity change (during rise time)	-	27 ft/s (8.1 m/s)
Total velocity change	-	47 ft/s (13.6 m/s)
Head C.G. Peak Acceleration	-	91.7 g
$\Delta t = t2-t1$	-	36.8 ms
HIC	-	**512**
Head average acceleration	-	45 g
Head impact velocity	-	46 ft/sec
Head impact angle	-	69 degrees

SLED TEST 01008-15



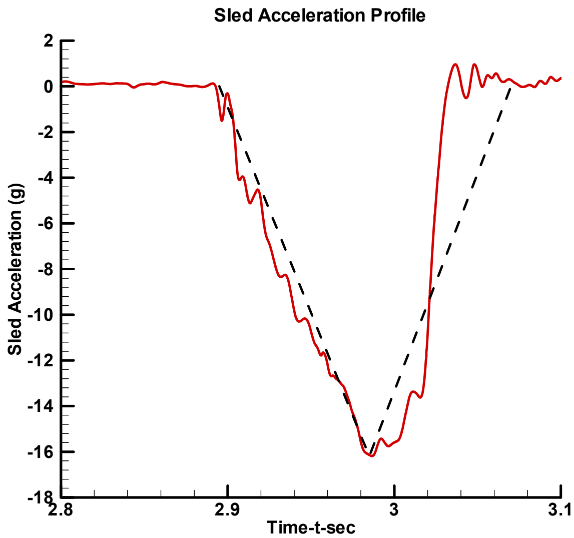


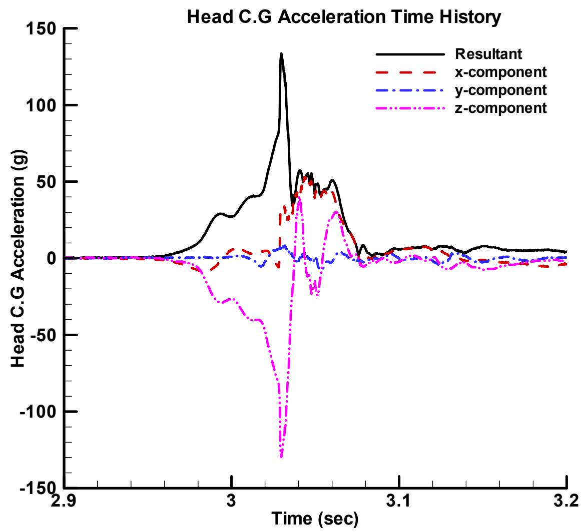


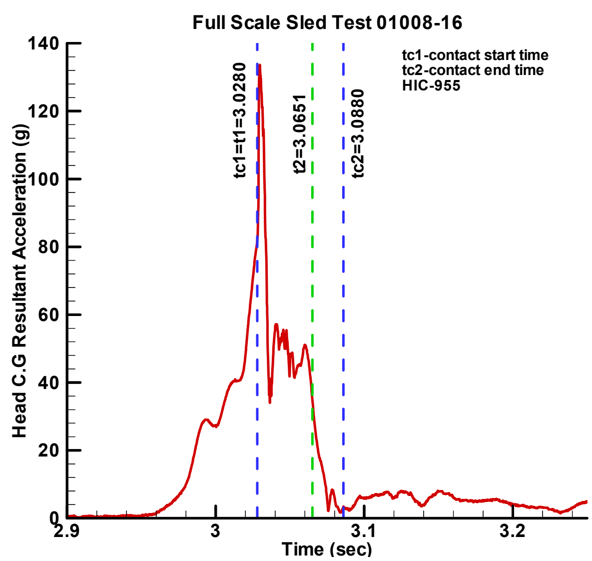
<u>Results of Sled test 01008-15</u>

Panel	-	TEKLAM - Aluminum honeycomb panel with fiberglass facing sheets 1 in. (2.54 cm)
Seat setback	-	35 in. (88.9 cm)
Peak sled deceleration	-	16.0 g
Rise time	-	86.2 ms
Velocity change (during rise time)	-	26 ft/s (8.1 m/s)
Total velocity change	-	44 ft/s (13.6 m/s)
Head C.G. Peak Acceleration	-	103.2 g
Δt = t2-t1	-	23.8 ms
HIC	-	**496**
Head average acceleration	-	58 g
Head impact velocity	-	53 ft/sec
Head impact angle	-	74 degrees

SLED TEST 01008-16







<u>Results of Sled test 01008-16</u>

Panel	-	TEKLAM - Aluminum honeycomb panel with fiberglass facing sheets 1 in. (2.54 cm)
Seat setback	-	33 in. (88.9 cm)
Peak sled deceleration	-	16.2 g
Rise time	-	87.8 ms
Velocity change (during rise time)	-	25 ft/s (8.0 m/s)
Total velocity change	-	44 ft/s (13.7 m/s)
Head C.G. Peak Acceleration	-	133.6 g
Δt = t2-t1	-	37.1 ms
HIC	-	**955**
Head average acceleration	-	58 g
Head impact velocity	-	46 ft/sec
Head impact angle	-	60 degrees

APPENDIX D—DESIGN METHODOLOGY APPLIED TO THIN ALUMINUM PANELS

The methodology for the design of HIC-compliant bulkhead can be broken in three major steps:

1. Estimate the initial stiffness of the bulkhead
2. Compare the stiffness value with the limiting value from the design curves
3. Fabricate the bulkhead and conduct dynamic sled test(s) to confirm HIC compliance

A thin 28.5- x 31.0- x 0.063-in. Al 2024 T3 panel was used as an example to explain the design methodology.

D.1 Hybrid Analytical Methods to Estimate Stiffness of Aluminum Panel.

The deflection of a simply supported rectangular plate can be represented in terms of double trigonometric series. Consider a concentrated load P acting on a simply supported rectangular plate of dimensions shown in figure D-1.

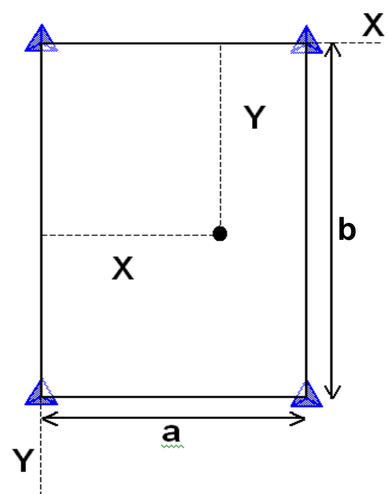


FIGURE D-1 SIMPLY SUPPORTED PLATE UNDER CONCENTRATED LOAD AT ANY POINT

The stiffness at any point on the plate is then given by the relation [12],

$$k = \frac{P}{W} = \frac{\pi^4 abD}{4\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \frac{\sin\left(\frac{m\pi\pi}{a}\right)\sin\left(\frac{n\pi\pi}{b}\right)}{\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2}\sin\left(\frac{m\pi\pi}{a}\right)\sin\left(\frac{n\pi\pi}{b}\right)}$$

Where,

P = Load
W = Deflection

D = EI = Bending Rigidity
E = Young's Modulus
I = Sec I = second Moment of Area
m , n = 1,3,5… (Convergence for three or four terms)

If the load acts in the center of a square plate then the equation reduces to,

$$k = \frac{D}{0.0112\, a^2}$$

The stiffness of the aluminum panel is calculated to be 591 lb/in at the center which is less than the threshold stiffness value of 709 lb/in for 35-in. seat setback configuration as per the design curves.

D.2 Finite Element Analysis of Aluminum Panel.

Figure D-2 shows the model developed in MSC-Patran used for the finite element analysis of a 2024 T3 aluminum panel. An aluminum bulkhead was modeled using solid 8-noded brick elements. A ball of mass 16 lb was used for impacting the aluminum panel and a gradual displacement is given to the ball. The ball was meshed using the shell elements. The boundary conditions were similar to the full-scale sled test. The analysis was run using LS-Dyna.

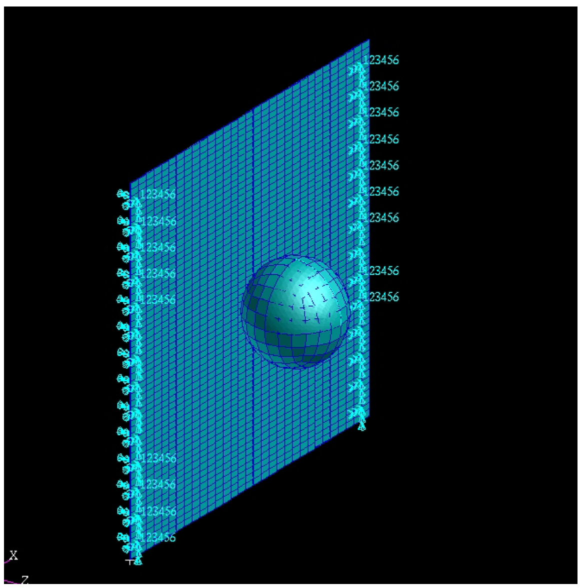


FIGURE D-2. FINITE ELEMENT MODEL OF THE ALUMINUM PANEL FOR THE BULKHEAD

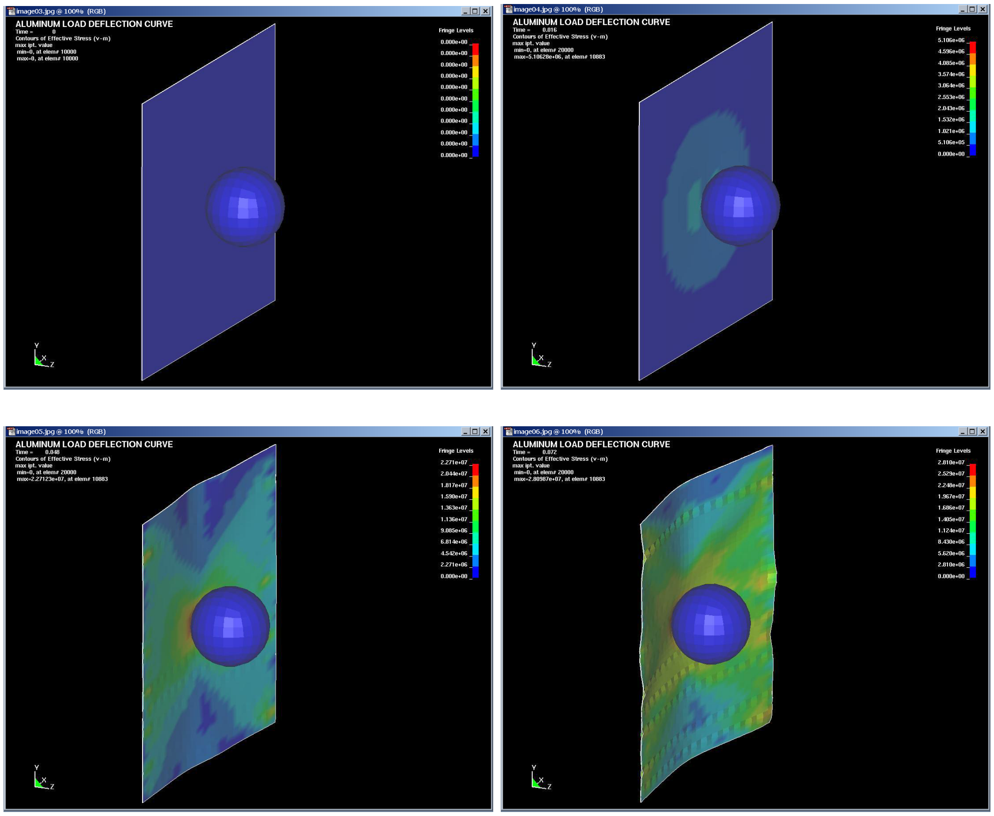


FIGURE D-3. STRESS DISTRIBUTIONS ON THE ALUMINUM PANEL

Figure D-3 shows the stress distributions in the aluminum panel at various time intervals during the analysis. The load and deflection data are obtained from the analysis and the stiffness of the panel is estimated. The stiffness calculated from the load-deflection curves obtained from the analysis is 605 lb/in.

D.3 Static Tests to Evaluate Stiffness.

Static tests were performed on Al 2024 sheet to obtain the load-displacement curves. This method is especially useful for bulkhead designs made of complicated material and/or boundary condition properties, for which the analytical or finite element techniques might not be suitable. Figure D-4 shows the setup for the static testing. The actuator assembly with the bowling ball attached to one end was used to apply the load. The weight of the bowling ball used for the static test was 16 lbs. A maximum load of 1500 lbs (approximately) was applied normal to the bulkhead at a point where ATD head is most liable to strike.

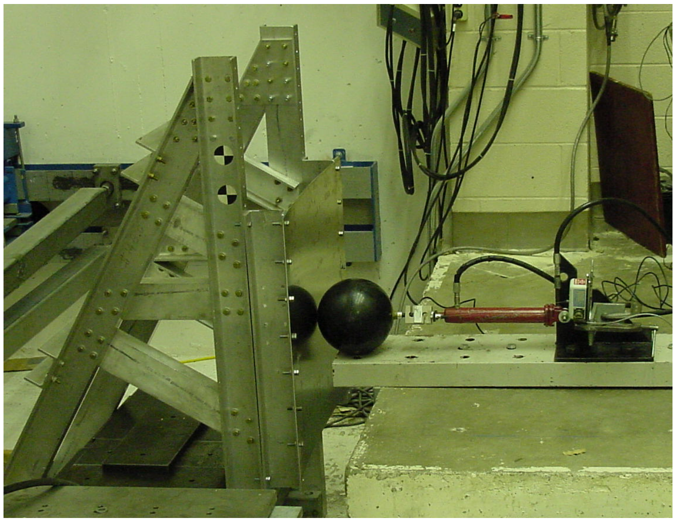


FIGURE D-4. TEST SETUP FOR STATIC TESTING ON ALUMINUM PANE

The load was gradually increased in small steps to a maximum applied load of approximately 1500 lbf at which there was a plastic deformation in the panel. Figure D-5 shows the load displacement characteristics obtained for the aluminum panel. The stiffness from the curve was 600 lb/in.

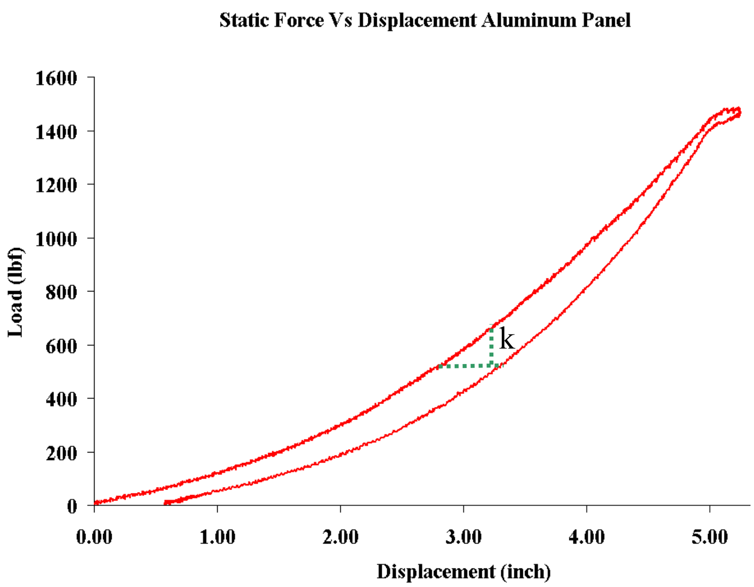
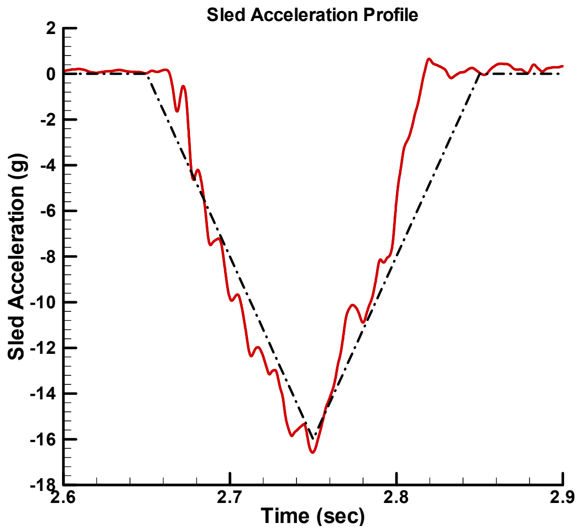
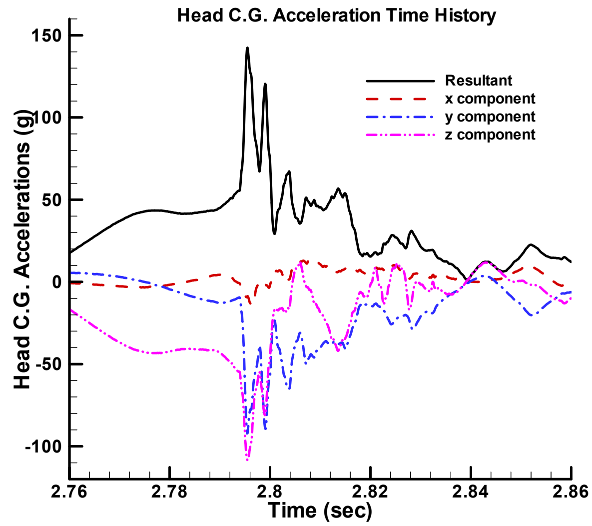


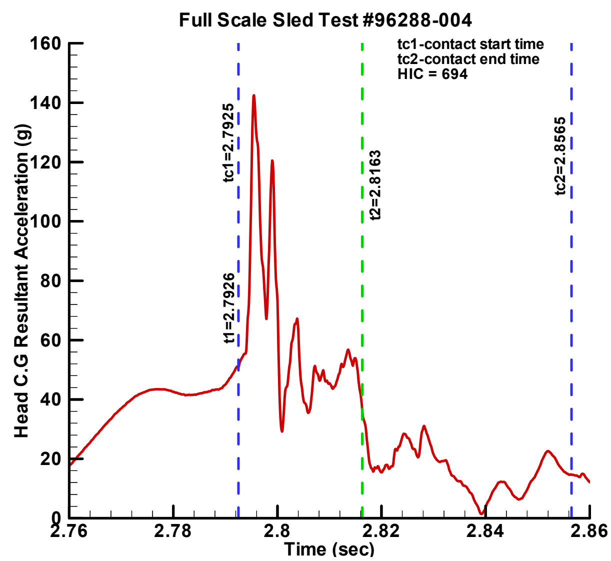
FIGURE D-5. LOAD DEFLECTION CHARACTERISTICS OF THE BULKHEAD SERIES

The stiffness value of the aluminum panel from all three methods is approximately 600 lb/in, and below the allowable threshold of 709 lb/in, which should result in HIC below the 1000 limit for a 35-in. seat setback distance. The corresponding HIC from the design curve or 35-in. seat setback distance is 860. Dynamic sled test 96288-004 was conducted on an Al 2024 T3 panel, which resulted in a HIC of 694. A detailed test summary is given in appendix E.

APPENDIX E—DATA SHEET FOR SLED TEST 96288-004







<u>Results of Sled test 96288-004</u>

Panel	-	2024-O Aluminum panel 0.063 in. (0.16 cm)
Seat setback	-	35 in. (88.9 cm)
Peak sled deceleration	-	16.6 g
Rise time	-	73.4 ms
Velocity change (during rise time)	-	30 ft/sec (9.27 m/s)
Total velocity change	-	46 ft/sec (14.05 m/s)
Head C.G. Peak Acceleration	-	142.5 g
Δt = t2-t1	-	23.7 ms
HIC	-	**694**
Head impact velocity	-	45 ft/sec
Head impact angle	-	38 degrees